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EFFECTIVE SAMPLING TECHNIQUES FOR PARTICULATE EMISSIONS FROM ATYPICAL STATIONARY SOURCES

Interim Report

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16. ABSTRACT

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Three specific sources--gravity roof ventilators, grain dryers, and wet scrubbers--were selected to provide the basis for the research program of the four atypical source categories. Basic characteristics of these sources were identified through literature and personal contact surveys. A program of model testing and field testing of roof ventilator emissions was completed, and a similar program was undertaken for wet scrubbers. The sampling strategy recommended for roof ventilator emission measurement on the basis of the test program includes a high volume particulate sampler and a heated thermopile anemometer deployed near the base of the ventilator.

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Interim Report

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ABSTRACT

Techniques and instrumentation for sampling strategies to measure particulate emissions from "atypical" stationary sources were developed. The four atypical source categories are low effluent streams, extended dimensions, partially or totally unconfined flow, and saturated gas streams or gas streams with entrained liquid droplets. The research program included literature surveys, laboratory model testing, and field testing of several atypical stationary sources. Techniques and instruments were evaluated as to the degree of reliability of measured emissions and applicability to general situations.

Three specific sources -- gravity roof ventilators, grain dryers, and wet scrubbers -- were selected to provide the basis for the research program of the four atypical source categories. Basic characteristics of these sources were identified through literature and personal contact surveys. A program of model testing and field testing of roof ventilator emissions was completed, and a similar program was undertaken for wet scrubbers. The sampling strategy recommended for roof ventilator emission measurement on the basis of the test program includes a high volume particulate sampler and a heated thermopile anemometer deployed near the base of the ventilator.

Future work will include the completion of test programs related to wet scrubbers and grain dryers. The implementation of these test programs will be based on the information gathered during the first year and presented in this interim report.

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I. INTRODUCTION

The capability to determine emission levels is of primary importance in any program intended to control emissions for two reasons. First, reliable emission levels must be established in order to assess the severity of an emission problem and, if necessary, set standards for its control. Second, in order to enforce compliance with established standards, emissions from a given source must be accurately determined. Procedures for selection of sampling sites, velocity measurements, and determination of particulate concentration have been established by the United States Environmental Protection Agency (Ref. 1) for emission sources characterized by well defined and constrained flow fields with velocities greater than 1.5 to 2 m/sec. Studies such as Ref. 2 have examined the reliability of emission measurements in sources, such as exhaust stacks and ductwork in large power plants, which fall into this category.

As programs to control emissions have met with success, more interest has been focused on emission sources in which the velocity, flow fields, and emissions are not well defined or the effluent gases are not confined. Emission sources of this nature are generally classified as "atypical". The intent of this study is to examine the emissions from sources characterized by one or more of the following:

1. low velocity (less than 2 m/sec);
2. one or more extended dimensions;
3. partially or totally unconfined flow;
4. saturated gas streams or gas streams with entrained liquid droplets.

Sampling techniques and strategies will be discussed for flow and particulate concentration measurement related to several specific atypical emission sources. The methods will be evaluated in regard to their usefulness for these specific applications as well as their applicability to other atypical sources.

The particular applications which will be discussed are roof ventilators (representing a low velocity/extended dimension source), grain dryers (partially unconfined flow) and wet scrubbers (entrained liquid droplets). Although both roof ventilators and grain dryers may be classifed as having characteristics under Items 1, 2 and 3, these sources were chosen as primarily representative of the indicated characteristics for determination of sampling techniques.

Having identified these specific applications as representative of the various atypical source categories, the basic procedure followed in investigating each emission source was as follows:

1. Identification of typical characteristics of the source through preliminary field testing;
2. Design and fabrication of a representative model of the source;
3. Testing of sampling techniques in the controlled model environment, identification of a useful sampling technique, and evaluation of accuracy;
4. Final field tests, if necessary, to confirm the applicability of the sampling technique to actual field situations;
5. Assessment of the applicability of the selected sampling technique to other atypical sources.

An overall evaluation of atypical emission sources will be presented first, followed by a discussion of the implementation of the above program for each of the selected sources.

II. CLASSIFICATION AND EVALUATION OF ATYPICAL EMISSION SOURCES

A survey of a number of atypical emission sources was made in order to determine which of the characteristics of interest apply to the various sources and, furthermore, to attempt to rank these sources in importance for consideration in this study. Information was extracted from the general literature as well as from contacts with instrumentation manufacturers, commercial firms engaged in emission measurements, and eight state pollution agencies in eight different EPA regions.

Table 1 includes a list of several atypical emission sources and classifies them with respect to the various characteristics. The term "low velocity" here refers to sources having emission stream velocities which may often be less than 2 m/sec. Sources such as roof ventilators and louvered panels confine the flow for a short path length and are characterized here as "partially confined". The distinction is drawn between partially confined sources and unconfined sources, such as open field burning or agricultural tilling. Brief descriptions of some of the sources outlined in Table 1 and evaluations of the degree of importance of the various sources are included in the following.

A. Emission Sources with Low Velocity and/or Extended Dimensions

1. Partially Confined Emission Sources

Several partially confined emission sources are listed in Table 2 together with information extracted from Refs. 3 through 8 concerning emission characteristics of these sources. Such sources are often also characterized by one or more extended dimensions and low velocity effluent streams, as are the sources listed in Table 2. The particular configuration of each source type, however, will usually establish one or two of these characteristics as the primary factor or factors in defining a sampling technique.

a. Roof Ventilators

Roof ventilators as emission sources are found in a number of industrial applications, some of which are indicated in Table 2. Continuous gravity ventilators are typically utilized in situations requiring the removal of large heat loads. Basically, two styles of gravity ventilators are marketed commercially. Figures 1 and 2 illustrate the two basic types. The type with a single emission plane (Fig. 1) may extend along the entire length of a building and is generally referred to as a "continuous roof ridge ventilator", while the two-channel

TABLE 1

CLASSIFICATION OF SOURCES WITH RESPECT TO EMISSION MEASUREMENT PARAMETERS

Source	Low Velocity	Extended Dimensions	Confinement			Saturated Gas	Liquid Droplets	Weather Sensitive
			Duct	Partial	None			
Roof ventilators	x	x		x				x
Grain dryers	x	x		x				x
Wigwam incinerators	x			x				x
Unload grain box cars-trailer trucks into deep hoppers	x	x		x				x
Agricultural tilling	x	x			x			x
Unpaved road dust	x	x			x			x
Open field burning	x	x			x			x
Construction and land excavation	x	x			x			x
Open baghouses	x	x			x			x
Open incinerators	x	x			x			x
Mining and quarry activities	x	x			x			x
Aggregate stockpiles	x	x			x			x
Handling & transfer at:								
Grain elevators	x	x			x			x
Cotton gins	x	x			x			x
Cement plants	x	x			x			x
Asphalt plants	x	x			x			x

TABLE 1 (CONT'D)

Source	Low Velocity	Extended Dimensions	Confinement Duct	Confinement Partial	Confinement None	Saturated Gas	Liquid Droplets	Weather Sensitive
Open vats	x	x			x	x		
Wet scrubber outlets			x			x	x	
Absorber exhaust sulfuric acid plants			x			x	x	
Saturators and blowers-asphalt roofing mfg.			x			x	x	
Paint booths			x			x	x	
Industrial dryers, e.g. plywood veneer dryer			x			x		
Ventilators emitting oil mist, e.g., machine shop, underground construction			x			x	x	

TABLE 2

PARTIALLY CONFINED EMISSION SOURCES

Source	Velocity at Plane of Emission m/sec.	Avg. Particulate Loading gm/m^3	Particulate* Size	Emission Rate Factor gm part per Kg of product	Estimated Total Annual Emissions metric tons
Roof Ventilators**	0.5 - 5				
1) Aluminum mill reduction cells					
a) H.S.Soderberg		0.07-4.6	Range down to submicron	72	32,000
b) V.S.Soderberg				42	9,100
c) Prebake				32	18,200
2) Open hearth steel furnaces					306,000
a) No oxygen lancing		0.9	50% $< 5\ \mu$	4	
b) With oxygen lancing		3.4	45% $< 5\ \mu$	11	
3) Electric arc steel furnaces					16,500
a) No oxygen lancing		0.2-5	60% $< 5\ \mu$	5	
b) With oxygen lancing		2.3-25	60% $< 5\ \mu$	5	
4) Iron Foundary furnaces		2.3-7	10% $< 5\ \mu$	8	100,000
Grain Elevators					
1) Grain Dryers	~3	9-80	Geo. means Oats 3.1 μ Wheat 2.1 μ	3-3.5	35,000
2) Grain loading/ unloading		0.25		1.5	110,000
Wig-Wam incinerators	~3	0.39	24% $< 2\ \mu$	5	120,000

* Size distribution information based on % by weight less than stated size.

** The figures tabulated represent total emission quantities through all controls and exhausts for the activities listed and are included in order to establish their relative importance.

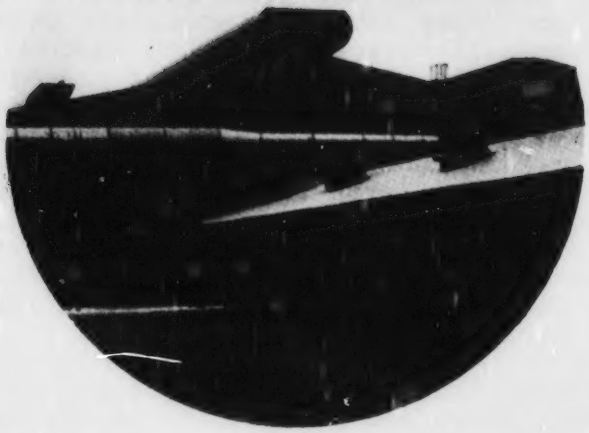


FIGURE 1. CONTINUOUS ROOF RIDGE VENTILATOR

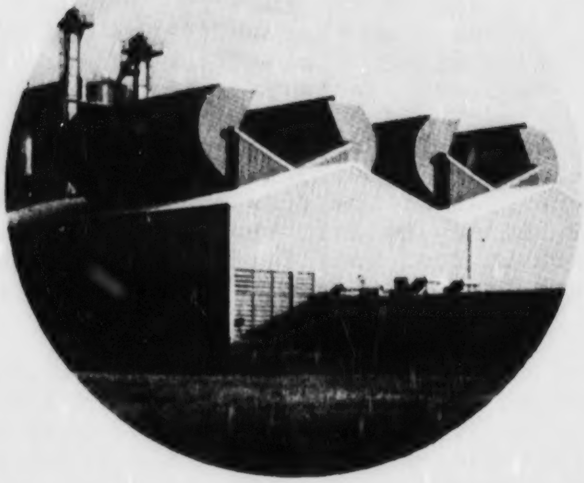


FIGURE 2. ROOF "MONITOR" OR "MONITOR ATTACHMENT"

exhaust style (Fig. 2) is usually denoted by the terms "monitor" or "monitor attachment". The term "roof monitor" however, is often used as a description of either style of gravity ventilator or even certain types of powered ventilators.

Gravity ventilators find application in steel and aluminum mills, foundries, forge shops and glass plants, as well as warehouses, zoos, and other locations where air conditioning units are not economically practical due to large heat loads and/or large interior spaces. Both types of pre-built ventilators, continuous roof ridge ventilators and roof monitors, are commercially available in 10 ft. lengths which may be spliced together to form runs of any desired length. The continuous roof ridge ventilator is available in sizes having throat widths ranging from 4 in. to 15 ft. and heights of less than 1 ft. to 18 ft. above the roof peak. The monitor type is available with openings ranging from 3 ft. to 15 ft. Both types are equipped with dampers which can be opened or closed to exhaust or retain building heat as required.

Roof ventilators often extend along the entire length of a roof ridge. Heat, fumes and particulate matter which evade primary control devices are propelled upward with thermal currents and may be emitted through the roof ventilator, which may often be considered a line source due to the large length dimension involved. The volume of emissions is dependent upon wind speed, temperature, building design, louver adjustment, and level of activity in the ventilated area. Table 3 is a sample from a manufacturer's bulletin (Ref. 9) which illustrates the effects of temperature, height, and wind speed on flow capacity through a roof ventilator. Such tables are generally calculated on the assumption of wind direction perpendicular to the ventilator length, based on the negative pressure which develops as the flow passes over the ventilator and creates an aspirating effect. Winds directed along the length of a ventilator will have much smaller effects than indicated in Table 3.

Certain general principles for roof ventilator design and performance calculations are specified in handbooks, such as Ref. 10. Detailed analyses of the flow are not available, however. In general, it may be said that flow rate and particulate concentration in roof ventilator exhausts are poorly understood, due to the large number of factors which affect performance.

An indication of the importance of roof ventilators as an emission source is given by Tables 4 and 5. This information was extracted from Ref. 11, which is a study of only one of the industrial applications listed in Table 2, the primary aluminum industry. This data is based on a survey of aluminum production facilities throughout the United States. As indicated in Tables 4 and 5, since the primary collection efficiency of most

TABLE 3

PERFORMANCE TABLE FOR GRAVITY ROOF VENTILATORS (Ref. 9)

Temp. Diff.	Stack Height	C.F.M. Per Square Feet of Ventilator Throat Opening At Wind Velocities of: 2 MPH	4 MPH	8 MPH	10 MPH
10°F	10 ft.	193	281	395	457
	20	236	324	438	500
	30	271	359	473	535
	40	298	386	500	562
	50	323	411	525	587
20°F	10 ft.	236	324	438	500
	20	298	386	500	562
	30	345	433	547	609
	40	385	473	587	642
	50	414	502	616	678
30°F	10 ft.	271	359	473	535
	20	345	433	547	609
	30	403	491	605	667
	40	451	539	653	715
	50	494	582	696	758

1 foot = .3048 meters

TABLE 4

INDUSTRY REPORTED EMISSION DATA FOR PRIMARY ALUMINUM FACILITIES (Ref. 11)

	% Capacity Reporting	Kg Particulate/Metric Ton Aluminum		
		high	average	low
Prebake Potlines				
Total effluent	60	88.6	47.2	22.5
Primary collection	83	84.5	43.8	21.6
Secondary collection	65	7.8	4.0	2.0
Primary emission	76	12.5	4.6	1.1
Secondary emission	65	7.8	4.0	2.0
Total emission	65	16.3	8.1	3.5
Overall control efficiency			81%	
Vertical Stud Soderberg				
Total effluent	--	----	39.2	----
Primary collection	--	----	22.0	----
Secondary collection	--	----	11.0	----
Primary emission	89	6.5	4.4	2.2
Secondary emission	--	----	6.7	----
Total emission	--	----	11.7	----
Overall control efficiency			70%	
Horizontal Stud Soderberg				
Total effluent	93	52.0	49.2	41.8
Primary collection	93	42.0	39.1	31.4
Secondary collection	93	10.4	10.1	10.0
Primary emission	93	10.1	8.9	8.5
Secondary emission	93	10.4	10.1	10.0
Total emission	93	20.5	19.0	18.5
Overall control efficiency			61%	

TABLE 4 CONT'D

	% Capacity Reporting	Kg Particulate/Metric Ton Aluminum		
		high	average	low
All types				
Total effluent	63	88.6	47.7	22.2
Primary collection	82	84.5	40.3	16.4
Secondary collection	71	7.8	6.9	2.0
Primary emission	82	24.4	5.9	1.1
Secondary emission	71	7.8	6.4	2.0
Total emission	71	23.5	12.3	3.5
Overall control efficiency			73%	

TABLE 5

SUMMARY OF EMISSION DATA-
PRIMARY ALUMINUM INDUSTRY (Ref. 11)

	Emission Factor Kg Particulate/Metric Ton Aluminum			
	Prebake	V. S.	H. S.	All types
Total effluent	47.2	39.2	49.2	47.7
Primary emission	4.6	4.4	8.9	5.9
Secondary emission	4.0	6.7	10.1	6.4
Secondary collection	4.0	11.2	10.1	6.9
Portion of total effluent emitted through roof monitor	8.5%	17.1%	20.5%	13.4%
Efficiency of secondary (roof monitor) control	50%	63%	50%	52%

aluminum process facilities is quite high and secondary collection is either very low in efficiency or nonexistent, the particulate emission through roof ventilators generally equals or exceeds the total emissions from primary particulate control systems. Table 6 includes data, extracted from Ref. 11, related to EPA tests of a single vertical stud Soderberg potline, which indicates similar conclusions.

b. Grain Drying and Handling

A number of partially confined emission sources are found in the grain and feed industry, one of which is grain drying. Grain drying is required when the moisture content of grain received at an elevator is too high for the grain to be safely stored. Drying is normally required when handling corn, although many other grains may require drying under certain conditions. Two common types of grain dryers, rack and column dryers, are illustrated in Fig. 3. Heated air is generally used as the drying medium, and newer grain dryer designs often incorporate continuous recirculation of a portion of this heated air for higher drying efficiency.

A survey of grain elevators in 1973 indicated that roughly 1.6 million bushels of grain are dried annually (Ref. 6). Contacts with agricultural associations and pollution control agencies indicated that virtually all corn elevators use grain dryers, while dryers are not as prevalent in handling wheat and other types of grain. Overall, grain dryers are found to have a large degree of application.

Emission levels for grain dryers, extracted from Ref. 6, are indicated in Table 7. Several other emission sources in the grain and feed industry, such as headhouses, are indicated in Ref. 8 as having higher total annual emissions than grain dryers. However, grain dryers present unique problems in emission measurement due to the large surface area of the emission plane, low velocities, and large particulate size (Ref. 6). While reliable emission measurements have been obtained for most emission sources in the grain and feed industry using Method 5 equipment and techniques, emission data for grain dryers has been shown to be very unreliable due to these sampling problems.

In additon to hulls, cracked grain, weed seeds, and field dust, grain dryer emissions include other large, lightweight particles denoted as "chaff", or "beeswing" in the case of corn, which break off from the grain during drying and handling. The low specific gravity of emitted particulate matter intensifies the sampling and collection problems associated with the partially unconfined nature of grain dryers as an emission source. The emission level is affected by a number of factors,

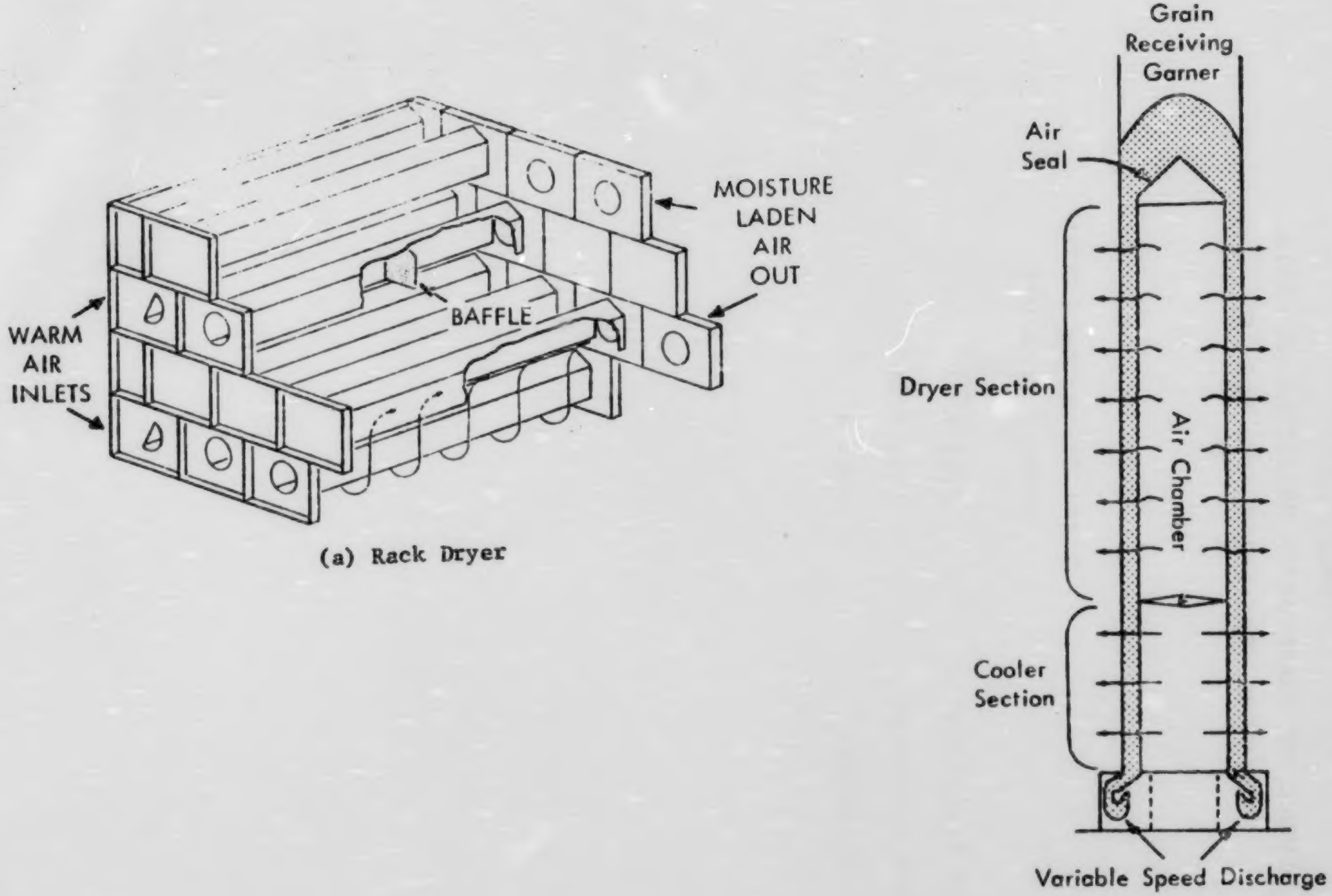
TABLE 6

EMISSION FACTORS FOR A VERTICAL STUD SODERBERG POTLINE - EPA TEST RESULTS (Ref. 11)

	Emission Factor kg Particulate/Metric Ton Aluminum (1)	(2)
Primary collection	45.63	33.80
Secondary collection	13.56	13.34
Primary emission	0.06	0.06
Secondary emission	4.77	2.92
Total emission	4.83	2.97
Primary efficiency	99.86%	99.84%
Secondary efficiency	64.85%	78.15%
Overall efficiency	91.85%	93.70%

(1) Average of 3 tests.

(2) Average of 2 tests; 1 test deleted due to stud blow during test.


WARM
AIR
INLETS
BAFFLE
MOISTURE
LADEN
AIR
OUT
Grain
Receiving
Garner
Air
Seal
Dryer Section
Air Chamber
Cooler
Section
Variable Speed Discharge

(a) Rack Dryer

(b) Column Dryer

FIGURE 3. RACK AND COLUMN TYPE GRAIN DRYERS (FROM REF. 6)

TABLE 7

SUMMARY OF GRAIN DRYER EMISSIONS AT GRAIN ELEVATORS (Extracted from Ref. 6)

	Total Emissions (1971) (metric tons/yr)
Country Elevators	2.14×10^4
Terminal Elevators	2.53×10^3
Export Elevators	3.82×10^2

including the type of dryer, the type and hardness of the grain, the moisture content of the grain (typically 10-20%) and the amount of foreign material in the grain.

Another partially confined source related to grain elevators is the deep receiving hopper. Grain is dropped from boxcars or trucks in surges from a height of 1 to 5 m (Fig. 4). The falling grain particles disperse as they accelerate and induce into motion a column of air moving in the same direction. When the mass of particles strikes the hopper bottom, the dissipated energy results in extreme turbulence as well as abrasion and dispersion of the particles. The dust generated may form a plume of 100% opacity and sufficient volume to envelope an entire boxcar. Sampling of such sources is usually accomplished by assessment of the ambient conditions.

c. Incinerators

Incineration of sawmill wood and bark wastes is a primary air pollution source in the lumber industry. Effluent gas velocities from wigwam incinerators may be on the order of 3 m/sec. Air quality problems may often be reduced by improvements in combustion efficiency.

2. Unconfined Emission Sources

Emission sources from which the pollutants are not constrained by process streams are classified as unconfined sources. Unconfined, or fugitive, emissions are generated by natural means as well as industrial processes. Dust arising from wind erosion has been estimated to comprise 20% of the total annual worldwide aerosol production (Ref. 13). Fugitive dust sources are now being recognized as possible causes for regional noncompliance with air quality standards.

Several activities which may generate unconfined emissions are summarized in Table 8. The data presented in this table was extracted from Refs. 3 and 5. For many unconfined emission sources, published data is either of a qualitative nature or is unavailable.

a. Stone Crushing and Asphalt Plants

Fugitive emissions in the stone crushing industry can be generated by activities such as drilling, blasting, crushing, conveying, removal of fines, storage and loading. Most emissions are of heavy particles that settle near the source. Crushing is done in three stages, and the third crushing and screening processes contribute the major portion of the emission. The degree of enclosure of the processing and transfer

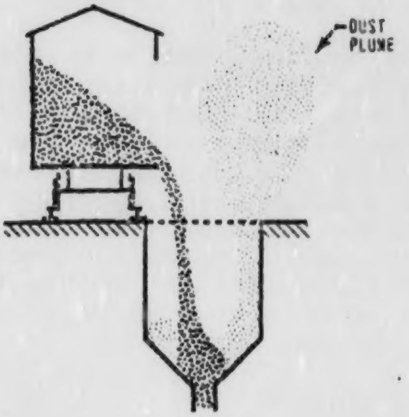


FIGURE 4. UNLOADING GRAIN FROM BOX-CAR INTO A DEEP HOPPER (REF. 12)

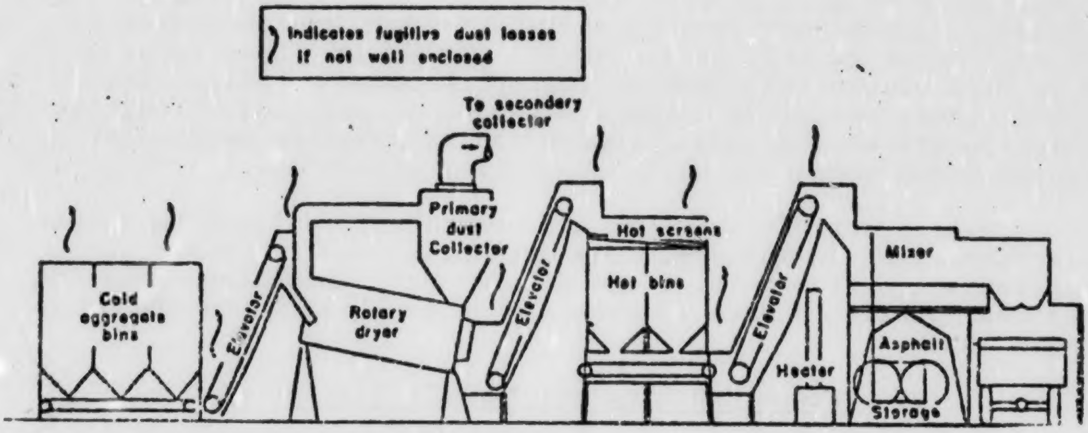

Indicates fugitive dust losses if not well enclosed
To secondary collector
Primary dust Collector
Cold aggregate bins
Elevator
Rotary dryer
Elevator
Hot screens
Hot bins
Elevator
Heater
Mixer
Asphalt
Storage

FIGURE 5. UNCONFINED EMISSION SOURCES AT A CONTINUOUS MIX ASPHALT PLANT (REF. 5)

TABLE 8

UNCONFINED EMISSION SOURCES

Source	Average Particulate Concentration gm/m^3	Particle Size	Emission Rate Factor gm Particulate per kg Product	Estimated Total Annual Emissions metric tons
Crushing				
a) Stone	-	10-50μ*	8	4,150,000
b) Sand & Gravel	13-87	3.5-9.4μ*	0.05	42,000
Asphalt Plants	-	40%<10μ***	4	37,000
Agricultural Field Burning	.01-.06	0.5μ*	8.5	2,200,000
Cement Plants	2-35	30%<5μ***	26	172,000
Cotton Gins	.004-1.25	-	5kg/bale	41,000
Aggregate Stockpiles	-	-	0.1-0.5%**	6,000,000

* Typical mass median diameter.

** Stockpile losses due to wind erosion.

*** Size distribution information based on % by weight less than stated size.

areas and the degree to which control equipment is used in the various processes determine the quantity and concentration of emissions. Possible fugitive emission sources at asphalt plants are indicated in Fig. 5. Dust is generated at elevator transfer points, hot screens, and hot and cold aggregate bins.

b. Agricultural Burning

Smoke from agricultural field burning is composed primarily of carbon particles, ash, and various gases. These emissions cause reduction of visibility and odors. Emission plumes consist mostly of particles less than 1.3 microns in diameter, identified as medium-and large-molecule hydrocarbons which provide a serious potential for lung irritation (Ref. 14). Emissions from field burning are highly dependent on wind, ambient temperature and type of fuel being consumed. Slash burning, primarily practiced in the Western United States to reduce the flammability of heavy slash concentrations after timber cutting, has been estimated by the United States Department of Agriculture to produce 5.5 million metric tons of particulate each year.

c. Emission Measurements and Standards

A number of studies have been made concerning the prediction of plume heights and concentrations related to unconfined sources using various dispersion models. Actual measurement of emissions from unconfined sources is poorly defined, however. Most measurement studies have utilized ambient monitoring equipment located in the vicinity of an emission source, often upstream or downstream of the source in the direction of the prevailing wind.

Ref. 15 includes empirical equations for emission factors of four categories of unconfined sources (agricultural tilling, unpaved roads and airstrips, heavy construction activities and aggregate storage piles) which are based on an extensive field testing program. The testing reported in Ref. 15 included isokinetic dust exposure with specially designed sampling equipment, conventional high volume sampler measurements and particle size measurements with high volume cascade impactors. Emission factors were related to meteorological and source parameters including properties of the emitting surface and characteristics of the vehicle or implement which caused the emission, and correction factors were developed to reflect regional differences in climate and surface properties.

Emission standards for unconfined sources are generally of a qualitative nature. Regulatory agencies have normally adopted regulations prohibiting airborne particulate matter from crossing property lines. Enforcement of such regulations is generaly handled on a complaint basis.

B. Emission Sources with Saturated Gas Streams or Entrained Liquid Droplets

Effluent streams from certain industrial processes are characterized by saturation with various types of vapors or by the presence of entrained liquid droplets. Several emission sources of this type are listed in Table 9 along with emission data extracted from Refs. 3, 5, 8, 16, 17 and contacts with various information sources.

Cooling of exhaust gases from evaporators, boilers and stills below the dew point of any gaseous components, such as water or acid, can generate large quantities of liquid droplets. Wet scrubber control systems also introduce droplets into exhaust gases. Droplets formed by tearing of liquid sheets and ligaments and by splashing of liquid drops are generally 200 μ and larger. The mist formed by condensation of saturated vapor contains submicron droplets. Entrained liquid droplets may cause excessive corrosion, decrease in equipment performance, or loss of processed material in addition to the air pollution problems.

1. Sulfuric Acid Plants

The exhaust gases from sulfuric acid manufacturing plants are common sources of acid mist. Sulfuric acid is manufactured by either the chamber process or the contact process (Ref. 16). The primary emission source in the chamber process is the Gay Lussac Tower, whose function is to recover nitrogen oxides released in the manufacturing process. Aerosol concentrations may range from 0.2 - 1.2 gm/m^3. Over 90% of the particles, by mass, are larger than 3 μ in diameter.

The major emission source in sulfuric acid contact plants is the stack from the absorption tower, which removes most of the sulfur trioxide. Small amounts of unabsorbed sulfur trioxide and a larger quantity of acid mist are emitted to the atmosphere. The presence of a substantial number of particles smaller than 3 μ is evidenced by the appearance of a dense, white plume at the stack exit which does not necessarily reflect the mass concentration of sulfuric acid mist.

Several types of mist eliminators are used with varying degrees of success in removing the entrained droplets. Electrostatic precipitators and glass-fiber mist eliminators can achieve 92-99.9% collection efficiency over the entire particle size range. Stainless steel wire-mesh mist eliminators have low initial cost but have low efficiency during the production of oleum, a solution of free, uncombined sulfur trioxide, when the proportion of small particles is sharply increased. Tall stacks, on the order of 50 m or larger, have been shown to be effective in reducing acid spray emissions, since large particles

TABLE 9

EMISSION SOURCES WITH SATURATED GAS STREAMS OR ENTRAINED LIQUID DROPLETS

Source	Flow Rate Nm^3/min	Avg. Particulate Concentrations gm/m^3	Particle Size	Emission Rate Factor gm part per Kg of Product	Estimated Total Annual Emissions Metric Tons
Sulfuric acid plants					
Chamber process	55-370	0.2-1.2	10% < 3 μ**	2,5	1,800
Contact process	140-1750	0.04-1.75	64% < 3 μ**	1	3,600
Spent acid concentrators	1700	2-4	-	15	7,200
Asphalt Roofing Mfg.					
Blowers & Saturators	280-560	1.0-1.8	∿ 1μ	2	15,500
Plywood Veneer Dryers	-	-	-	$3\ \mathrm{Kg}/1000\ \mathrm{m}^2$	3,600
Wet Scrubber					
Downstream of Thermal Coal Dryer	600-5500	.070*	-	-	94,000*
Sewage Sludge Incinerators	850	0.3*			

* Estimate includes solid particulate.

** Size distribution information based on % by weight less than stated size.

tend to collect on the stack wall. Indications are that approximately 90% by mass of the total acid mist and spray from an absorber outlet has been collected in an 80 m stack.

2. Asphalt Plants

Another source of vapors and mists are the effluents from "blowing", or oxidizing of stills and saturators used in the manufacture of asphalt roofing. Blowing is accomplished by bubbling air through the liquid asphalt at a temperature of about 230-260°C for 8 to 16 hours. After blowing, asphalt is transferred to a saturation tank or spray area where it is sprayed onto one side of felt that is continuously fed from rollers. This is done in order to remove moisture from the felt which could cause blisters when the felt is saturated by passing it through a tank of molten asphalt.

The high application temperature causes vaporization of those asphalt components having lower boiling points. Moisture in the felt is also vaporized, which contributes to the formation of a mist of high opacity. Additional mists and vapors are emitted as the saturated felt is cooled. Particulate emitted from saturators is formed by condensation and, therefore, is likely to have a size on the order of 1 μ. Various hood and exhaust configurations have been devised for exhausting blower and saturator emissions which require volumetric capacities of 280-560 Nm^3/min.

3. Industrial Dryers

Industrial dryers are another source of vapor and liquid particulate emissions. Plywood veneer dryers are used to reduce the moisture content of green veneer panels from about 50% to less than 10% in long, heated, enclosed chambers. Dryer design varies greatly. Emission plumes are saturated with water vapor and other condensibles including wood resins, resin acids and wood sugars which form a blue haze when cooled. Volatile components include terpenes as well as unburned methane when gas-fired dryers are used. Emission factors are generally expressed in terms of pollutant weight per unit of surface area of 1 cm (or 3/8 in) plywood produced. Condensible compounds are estimated by Ref. 8 to contribute 63% of the emitted pollutant, while volatile compounds make up 37%.

4. Wet Scrubbers

Wet scrubbers have found application in a wide range of effluent control problems. There are many varieties of wet collectors, but they may generally be classifed as low energy or high energy scrubbers. Simple spray towers, packed towers, impingement tray scrubbers, and other configurations which operate with low pressure drop may be classified as low energy scrubbers. Efficiences can exceed 90-95%. Air pollution control systems for incinerators, fertilizer manufacturing plants, lime kilns, iron foundries, stone crushing operations, and clay product production commonly incorporate low energy scrubbers.

High energy, or Venturi, scrubbers incorporate a converging-diverging duct section to attain high gas stream velocity while scrubbing liquid is injected. Higher collection efficiency is realized, but the higher efficiency is accompanied by higher pressure drops requiring high power draft fans. Common applications for Venturi scrubbers include steel furnaces, pulp mills and foundry cupolas.

The three situations indicated in Table 9 are not representative of the large number of scrubber applications, but they do indicate the broad range of conditions which may be encountered in scrubber exhaust gases.

C. Selection of Sources for Test Program

After evaluating a number of emission sources, including the information presented in the previous sections as well as information found in Refs. 17-28, three specific sources were chosen for the test program. By limiting the actual test program to these specific emission sources, it was felt that a reasonable amount of useful information about each of the selected sources could be obtained within the alloted limits of the program. If the selected sources are sufficiently representative of the atypical source categories of interest, the test program should provide insight into sampling techniques for general emission sources possessing the various atypical source characteristics. The selected sources are discussed briefly in the following.

1. Roof Ventilators

Roof ventilators were selected as a representative example of two of the atypical source categories, emission sources characterized by (1) low velocity and (2) extended dimensions. The bases for this selection are the wide degree of application of roof ventilators, the significant emission levels associated with them and the clearly defined nature of the characteristics of the source (i.e., low velocity and extended dimension are clearly the outstanding features of roof ventilators).

2. Grain Dryers

Grain dryers were selected to represent the category of partially or totally unconfined flow. The choice of a partially confined source, rather than a totally unconfined source, was made in view of the overall philosophy of the program in regard to model studies. Modeling a partially confined emission source, such as a grain dryer, constitutes a reasonable extension of the sampling problem into the realm of this atypical source category without attempting to complicate matters to a degree which would very likely preclude any concrete results within the scope of the present study. The choice of grain dryers as the specific source was based on their common usage as well as the previously noted sampling difficulties cited by other investigators of grain dryer emissions.

3. Wet Scrubbers

The exhaust flow from wet scrubbers was chosen as the representative example of emission sources with saturated gas streams or gas streams with entrained liquid droplets. This choice was based on the popularity of scrubbers in pollution control systems and the resulting large number of applications in various industrial situations. In addition, the exhaust of a scrubber is generally a duct or stack, which lends itself well to modeling and laboratory testing.

III. ROOF VENTILATOR SAMPLING TECHNIQUES

Continuous gravity roof ventilators, in the typical application, are primarily characterized by low velocity and extended dimensions. These two characteristics make emission measurement following EPA Method 5 sampling techniques inadequate. Under the present study, sampling methodology which has been applied to roof ventilators was reviewed, and techniques and instrumentation for measurement of roof ventilator emissions were evaluated following a test program as outlined in the Introduction.

A. Review of Sampling Methodology

Contacts with a number of commercial firms which have performed emission measurements in roof ventilator applications revealed that specific procedures for such situations have not been established. In general, sampling techniques and instrumentation have been selected for a given application on the basis of engineering judgment. Sampling techniques have often employed temporary collection hoods of some type, and generally the use of high volume samplers has been prescribed for particulate collection. The most frequently used velocity instruments were vane or propeller anemometers, followed in preference by hot wire anemometers. Reliability of emission measurements has generally been considered poor due to the low velocity, fluctuating, often circulatory flow characteristic of roof ventilators as well as the intermittent nature and low concentration of the particulate emissions from most roof ventilators.

A study of roof ventilator emissions at electric furnace operations led to the development of test methodology by Kreichelt and Keller (Ref. 29). Particulate concentration measurements were accomplished using standard high volume samplers suspended inside the roof ventilators, and velocity measurements were obtained using both hot wire anemometers and rotating vane anemometers. In this study, emission measurements were determined for a 60 m long roof ventilator both during periods of changing and tapping of the steel furnaces and during periods of so called "background" emission. Several high volume samplers spaced at 8.5 m intervals along the ventilator length were operated simultaneously; during charging and tapping operations, the samples were fixed at the midpoint of the monitor width due to the short duration of these operations, while the samplers were traversed across the width during background measurements. Velocity traverses were made independently of particulate concentrations during charging and tapping operations, the total number of traverse points being dictated by the time duration of the operations. Background period velocity measurements consisted of 6 point traverses at each of the 7 sample locations.

Figure 6 indicates the sampling technique discussed in Ref. 29. No attempt was made to sample isokinetically due to the large velocity fluctuations observed. Variations as large as a factor of 6 were observed from point to point, yet overall average velocities from various surveys during the background periods agreed well. (The average sampling velocity did agree fairly well with the average effluent velocity.) An overall assessment of the test methodology in Ref. 29 concluded that it provided a technically feasible, but costly, method for determination of emissions from roof ventilators; the total time and cost estimate given in Ref. 29 was 4 months or more and $10,000-$20,000 to complete a single emission study.

Souka, et al (Ref. 30), described a sampling technique used to evaluate emissions from a 1.22 m x 91.5 m roof ventilator at a graphitizing facility. Three sampling systems (Fig. 7), each including a high volume sampler and an electric anemometer, were located at the midpoints of equal sections of the ventilator outlet. Baffle plates, roughly 3 m in length, were located about 3 m on each side of each sampling station to minimize wind crossflow effects.

The testing period reported in Ref. 30 was 160 hours of almost continuous sampling. Particulate collection filters were changed at times dictated by observing the decreasing flow rate through the samples. Velocity readings were obtained every 1.2 minutes and averaged over the appropriate sampling periods. Since isokinetic sampling could not be achieved due to the fluctuating effluent velocity, sampling rates were kept well below isokinetic rates in order to achieve conservatively high emission rate measurements. Emission rate determined by this method is indicated in Fig. 8 for one of the three sampling stations. The conclusion drawn from Ref. 30 is that the wide emission rate fluctuation observed dictates long sampling periods to obtain a true picture of actual emissions. Total cost for such an emission test were estimated to be on the order of $15,000-$25,000 (Ref. 31).

Federal regulations in regard to roof ventilator sampling were formulated in conjunction with emission standards for the primary aluminum industry in the form of EPA Method 14 (Ref. 32). This method substantialy follows the sampling method developed by Alcoa for roof ventilator sampling (Ref. 33). Particulate concentration measurements, following Method 14, are to be accomplished by means of a sampling network as outlined in Fig. 9. In this system, effluent gas is drawn through 8 nozzles, mounted near the center of the roof ventilator, to a manifold. The velocity through each nozzle, as measured with an S-tube inserted through the calibration holes shown in Fig. 9, is adjusted to the same value by means of blast gates or valves before emission measurements are made.

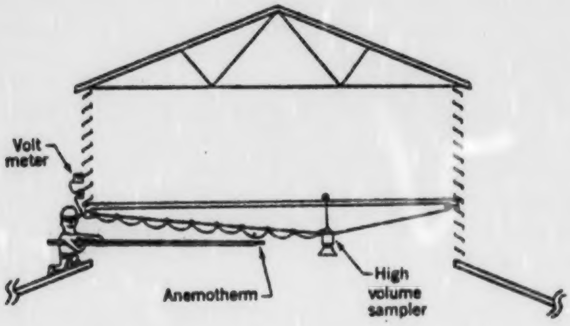

Volt meter
Anemotherm
High volume sampler

FIGURE 6. CROSS SECTION OF ROOF VENTILATOR SHOWING TEST EQUIPMENT (REF. 29)

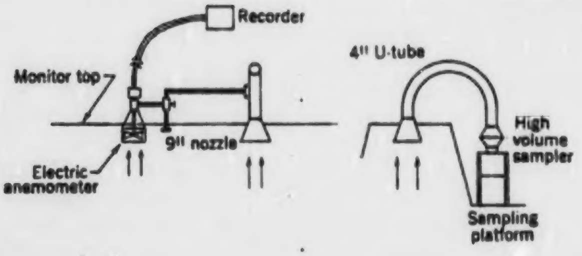

Recorder
Monitor top
9" nozzle
Electric anemometer
4" U-tube
High volume sampler
Sampling platform

FIGURE 7. SAMPLER SYSTEM (REF. 30)

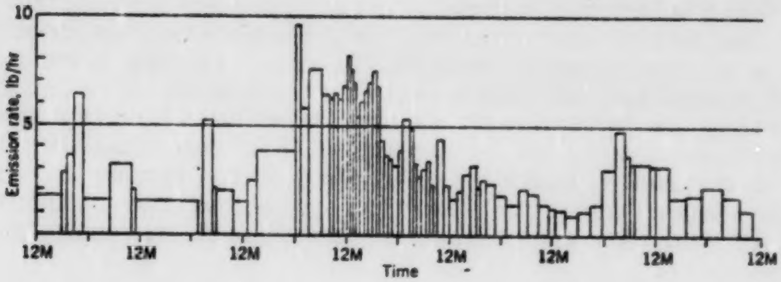


FIGURE 8. EMISSION RATE MEASUREMENTS, CENTRAL SAMPLING STATION (REF. 30)

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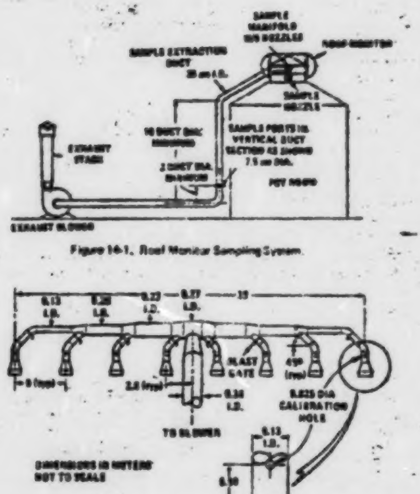

SAMPLE MANIFOLD (20 NOZZLES)
ROOF MONITOR
SAMPLE EXTRACTION DUCT
25 cm I.D.
SAMPLE NOZZLES
10 DUCT DIA. MINIMUM
2 DUCT DIA. MINIMUM
SAMPLE PORTS IN VERTICAL DUCT SECTION AS SHOWN 7.5 cm DIA.
POT ROOM
EXHAUST STACK
EXHAUST BLOWER
Figure 14-1. Roof Monitor Sampling System.
0.13 I.D.
0.20 I.D.
0.22 I.D.
0.27 I.D.
35
BLAST GATE
45° (typ)
3 (typ)
2.0 (typ)
0.34 I.D.
0.025 DIA CALIBRATION HOLE
TO BLOWER
DIMENSIONS IN METERS NOT TO SCALE
0.13 I.D.
0.10
0.20
0.15
0.64 I.D.

FIGURE 9. EPA METHOD 14 SAMPLING SYSTEM

Particulate sampling is then performed in the duct exhausting from the manifold. The length of the sampling manifold is to be 85 m or 8% of the total ventilator length, whichever is greater.

Velocity is to be determined by means of propeller or vane anemometers with electric output, appropriately protected from a dusty and corrosive atmosphere. One anemometer is required for each 85 m of ventilator length, located at the center of equal length segments and permanently mounted at a point of average velocity as determined by a widthwise velocity traverse. Velocity readings are to be recorded at maximum time intervals of 15 minutes during a test; the sample rate during a test is to be adjusted such that the velocity inlet to the sampling nozzles equals the average velocity determined for the 24 hours preceding the test.

All of these methods described in the literature emphasize particulate concentration measurement through the collection of relatively large sample volumes (compared to EPA Method 5), employing standard high volume samplers, modified high volume samplers, or specially constructed high volume nozzles and manifolds. Volumetric flow rates determined from single point measurements or widthwise velocity traverses at a small number of locations along the roof ventilator length together with the concentration measurements have been used in these methods to determine total emission rates. With the exception of the baffle plates in Ref. 30, artificial collection apparatus is not recommended in the literature, in contrast to the general impression received through commercial firm contacts.

B. Preliminary Field Tests

The site selected for field testing was Hitchcock Industries in Bloomington, Minnesota, a secondary aluminum foundry. This facility has a number of roof ventilators, both of the powered and natural draft type. The particular roof ventilators chosen for initial field testing are pictured in Fig. 10. Each of these ventilators is a 15.2 m (50 foot) length of a configuration known as the Swartwout (42 inch) Heat Valve. The ventilator height is approximately 2 m; the base width is roughly 2 m and the exhaust plane at the top is about 1.5 m wide. The ventilators shown in Fig. 10 are located above a room containing six gas-fired furnaces which are used to melt the aluminum stock. The roof ventilator exhaust configuration, which has two exhaust planes, is shown in Fig. 11.

Due to the expected low concentrations to be encountered, a high volume particulate sampler was chosen for the basic concentration measurement equipment. A Staplex Model TF1A high volume sampler was fitted with an extension probe and a 20.3 cm x 25.4 cm (8 inch x 10 inch) filter holder designed and fabri-

FIGURE 10. ROOF VENTILATORS AT HITCHCOCK INDUSTRIES, BLOOMINGTON, MINNESOTA, VIEWED FROM THE NORTHWEST.

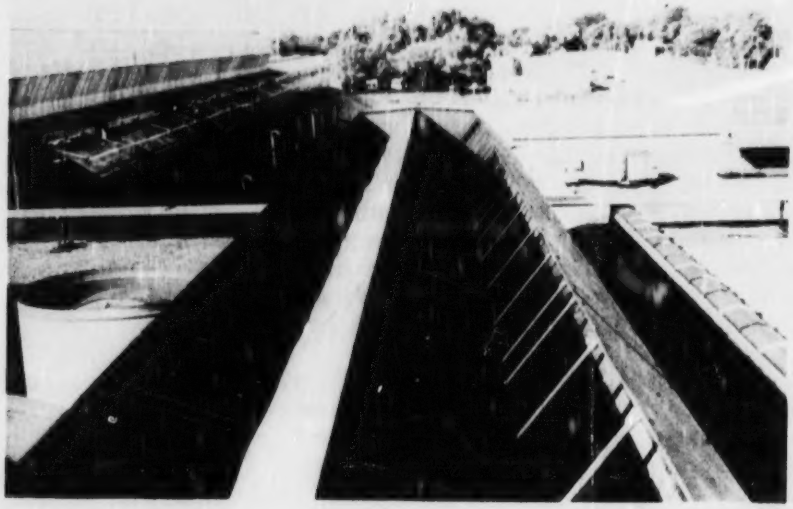


FIGURE 11. TYPICAL ROOF VENTILATOR EXHAUST AT HITCHCOCK INDUSTRIES SITE.

cated at FluiDyne facilities. The sampling probe is used with standard Gelman Type A glass fiber filters. The entire assembly is illustrated in Fig. 12. This sampling probe has a flow rate capacity as high as 2 m^3/min (70 ft^3/min).

The velocity instrumentation selected for the initial field tests consisted of a Thermo Systems, Inc. Model 1610 hot wire anemometer and a Flowrite Model MRF vane anemometer. The hot wire anemometer was fitted with a protective collar designed and built by FluiDyne (Fig. 13) for a previous project in which velocities in the range of 0.03 -4.57 m/sec (0.1 - 15 ft/sec) had been successfully measured. The vane anemometer was a direct reading instrument with a range of 0.3 - 15.2 m/sec (50 - 3000 ft/min). Both instruments were mounted on extensions to be hand held for the velocity measurements. The hot wire anemometer was also fitted with an iron-constantan thermocouple for temperature measurement.

During two days of testing at the Hitchcock Industries site, particulate concentration and velocity measurements were accomplished at several locations in one of the roof ventilators shown in Fig. 10. The sampling planes and locations are indicated in Fig. 14. Particulate concentration measurements were made at stations 2, 3 and 4, in both the east and west sample planes, and velocity surveys included measurements at all 5 sampling stations in both sample planes.

During the field tests, the operations within the foundry were also observed. The furnaces were loaded with aluminum of various degrees of quality, depending on the specifications of the various products being manufactured, to be melted down for pouring into molds. Scrap aluminum was sometimes melted, which often included foreign material such as steel wool. The furnace doors were often opened for brief periods during the melting process. The molten aluminum flowed from the furnaces into large vats. When the vats were full, the furnace doors were opened and the vats removed. In general, all six furnaces were not in use at one time; several furnaces often "idled" with the furnace doors open. The turnaround time for each furnace appeared to be roughly the same, thus keeping the overall level of activity generally fairly constant.

Visual observations of occasional plumes rising from the furnaces indicated that the flow was sometimes very turbulent, becoming well mixed by the time the roof ventilator was reached, and sometimes appeared much more uniform, rising steadily in a single column. In general, it was difficult to characterize the activities within the foundry by specific, scheduled operations, such as the charging and tapping operations described in Ref. 29. Overall, it was felt that the Hitchcock Industries site provided a good example of the type of problems to be encountered in studying roof ventilator emissions.

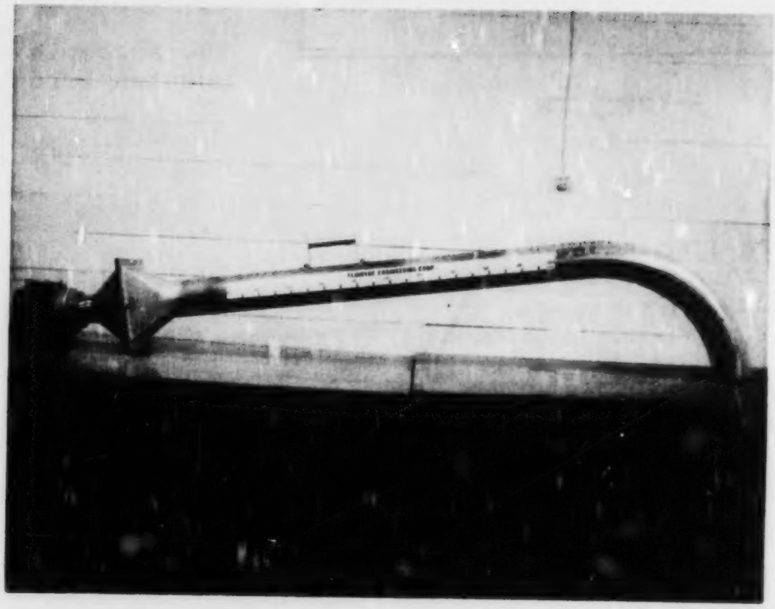
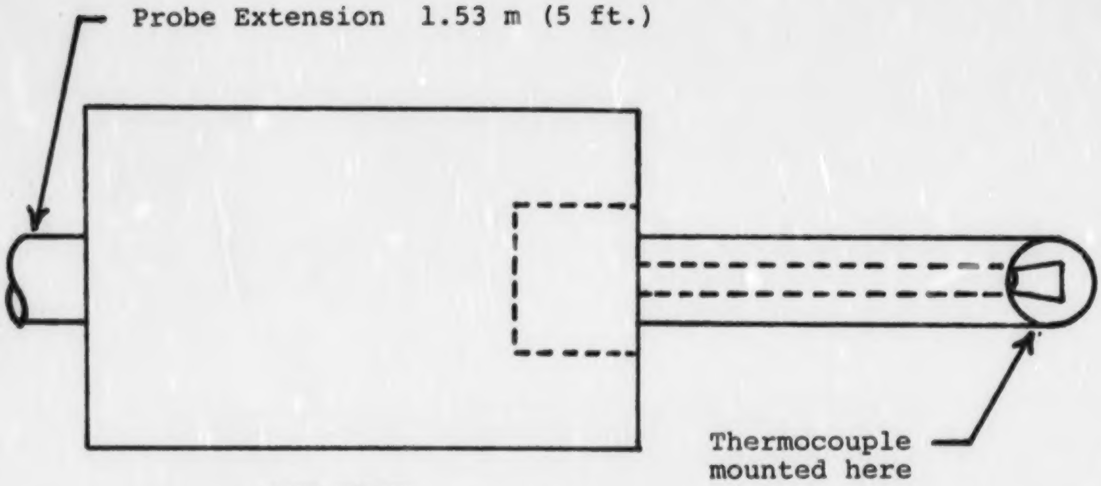
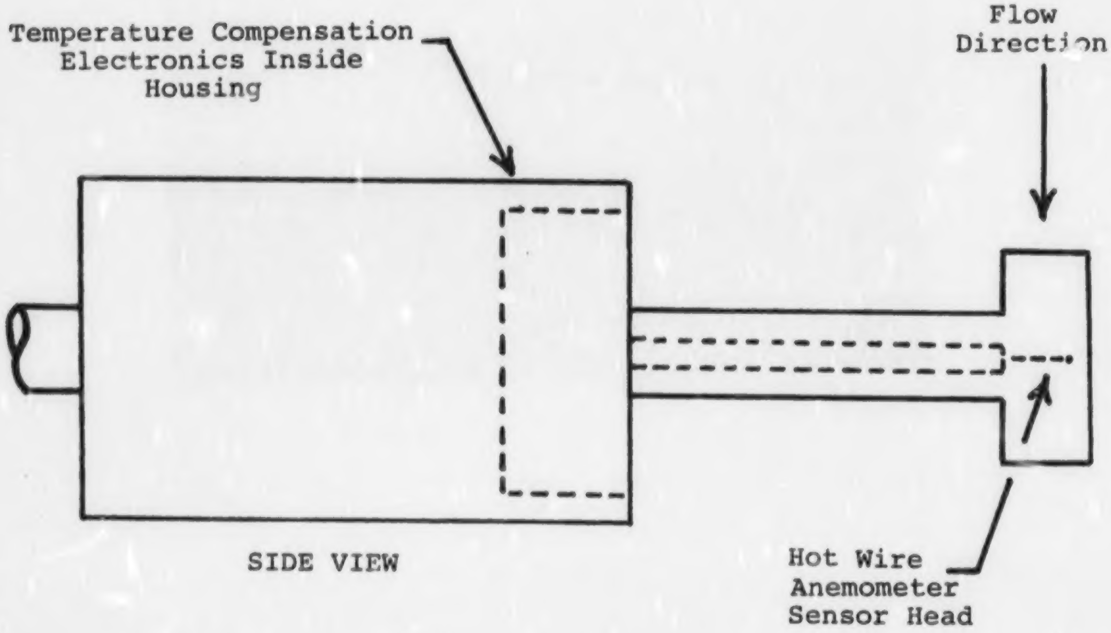


FIGURE 12. HIGH VOLUME SAMPLER AND PROBE ASSEMBLY


Probe Extension 1.53 m (5 ft.)
Thermocouple mounted here

TOP VIEW


Temperature Compensation Electronics Inside Housing
Flow Direction
Hot Wire Anemometer Sensor Head

SIDE VIEW

FIGURE 13. HOT WIRE ANEMOMETER AND PROTECTIVE COLLAR ASSEMBLY

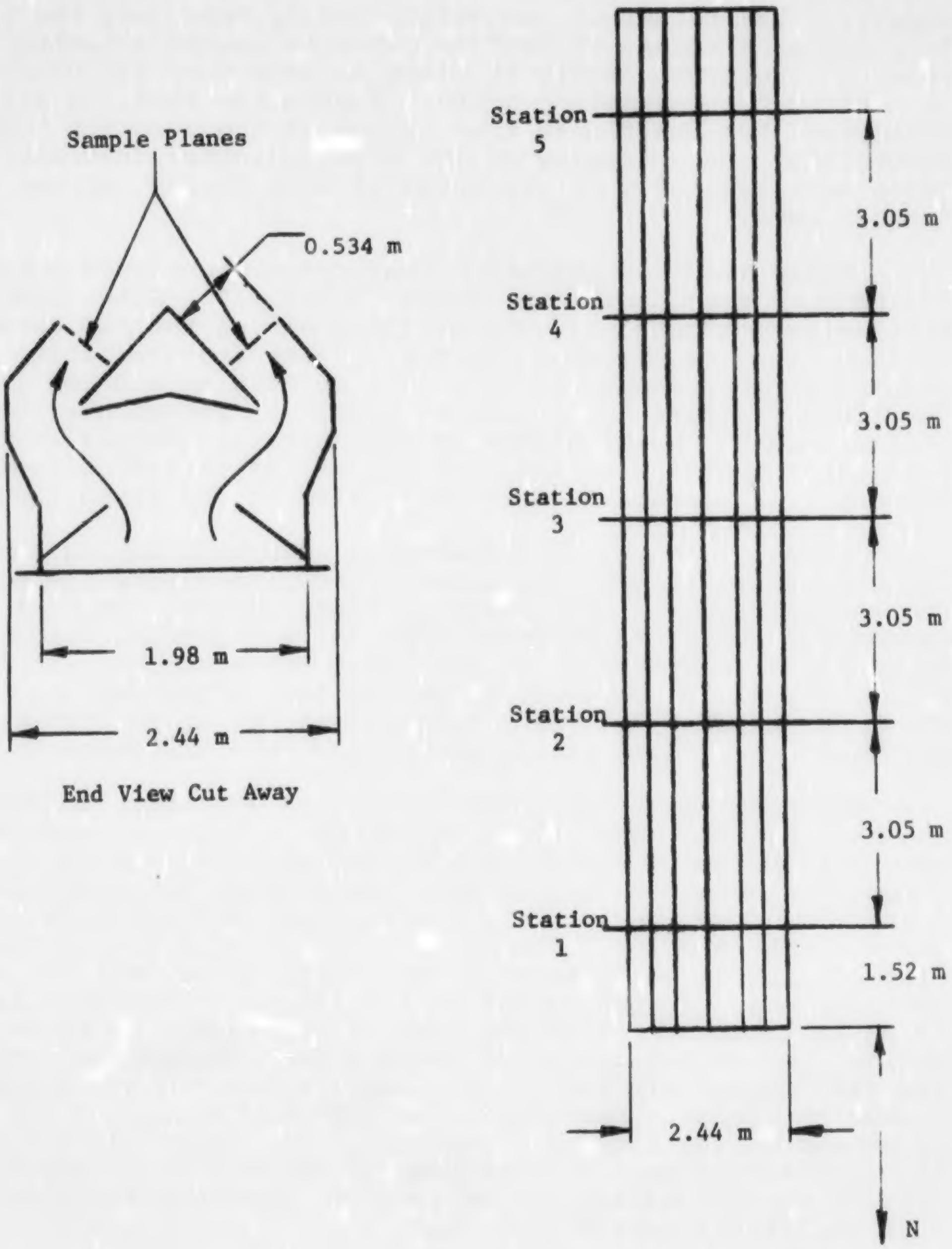

Sample Planes
0.534 m
1.98 m
2.44 m
End View Cut Away
Station 5
Station 4
Station 3
Station 2
Station 1
3.05 m
3.05 m
3.05 m
3.05 m
1.52 m
2.44 m
N

FIGURE 14

SAMPLING LOCATIONS FOR PRELIMINARY FIELD TESTS
HITCHCOCK INDUSTRIES ROOF VENTILATOR

The sample planes were chosen for maximum ease of alignment of the particulate sampling probe, as illustrated in Figs. 15 and 16. Samples were extracted for 90 minutes at a constant flow rate indicated by a rotameter mounted on the high volume sampler. The rotameter was calibrated by measuring the pressure drop across a series of orifice metering plates attached to the inlet of the probe nozzle in order to determine the actual flow rate through the sampling probe. Isokinetic sampling was attempted, but the fluctuating nature of the velocity made this impossible. Later review of the data indicated that sampling rates were typically in the range of 150% to 230% of the isokinetic rate.

Particulate concentration measurements obtained during the preliminary field tests are shown in Fig. 17. Since the measurements were extracted at various times during the two days of testing, the results shown in Fig. 17 are representative of several different activities in the furnace room below the ventilator. Thus, these results should be interpreted only as indications of the magnitude of concentration levels in the roof ventilator emission stream, and not as indications of possible concentration gradients which may exist at any given time.

Several velocity traverses were also made during the preliminary field tests. The measurement planes were the same as for the particulate concentration measurements. The hot wire anemometer proved to be unsuitable for the awkward conditions encountered; despite the special protective collar, the fragile wire tip was soon damaged, rendering the instrument inoperable. Thus, the bulk of the velocity measurements during the preliminary field tests were obtained with the vane anemometer.

The results of two velocity surveys are shown in Figs. 18 and 19. Although the velocities shown in Figs. 18 and 19 appear to be quite similar in the two surveys, the actual velocity fluctuated considerably about these plotted values determined from the velocity instruments, and the magnitude of the average velocity differed by a factor of 1.7. Different wind conditions were observed during these two velocity surveys, the component of wind normal to the length of the ventilator being 14 times larger in the case of the larger measured velocities. Other factors which could affect the exhaust velocity are the ambient air temperature and the temperature distribution inside the furnace room, which depends on the particular activities inside the foundry. Therefore, the velocity data shown in Figs. 17 and 18 must also be considered only as an indication of typical magnitudes and not definitive characteristics of the roof ventilator exhaust.

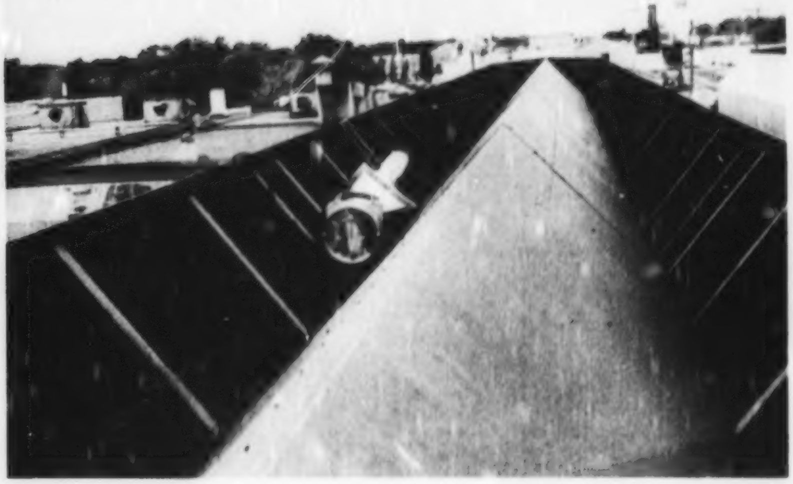


FIGURE 15. HIGH VOLUME SAMPLER ASSEMBLY MOUNTED IN THE ROOF VENTILATOR AT HITCHCOCK INDUSTRIES (END VIEW LOOKING NORTH)

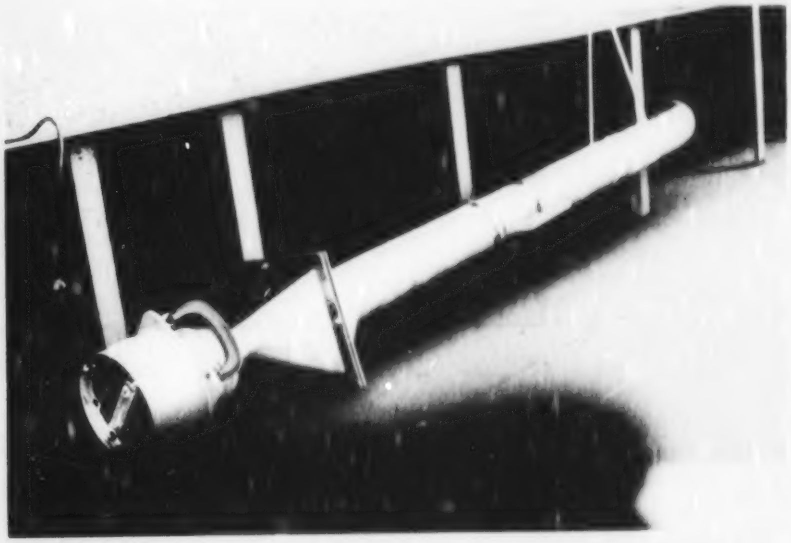
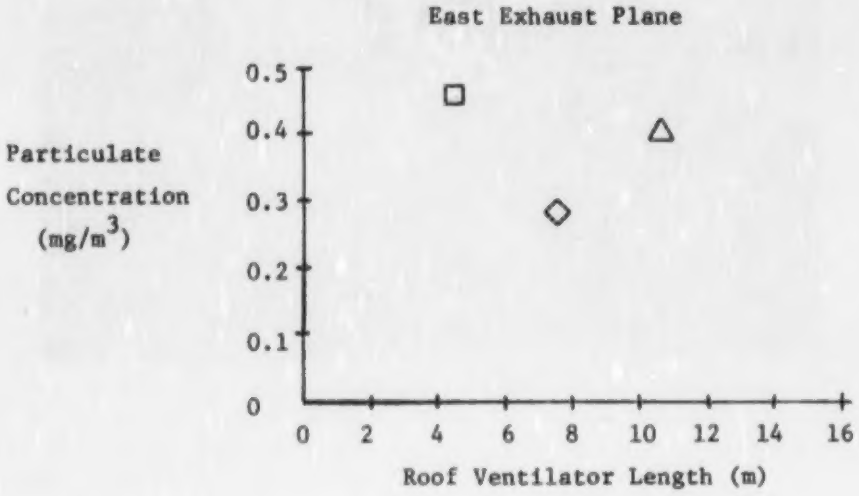


FIGURE 16. HIGH VOLUME SAMPLER ASSEMBLY MOUNTED IN THE ROOF VENTILATOR AT HITCHCOCK INDUSTRIES (TOP VIEW LOOKING DOWN INTO EXHAUST REGION)



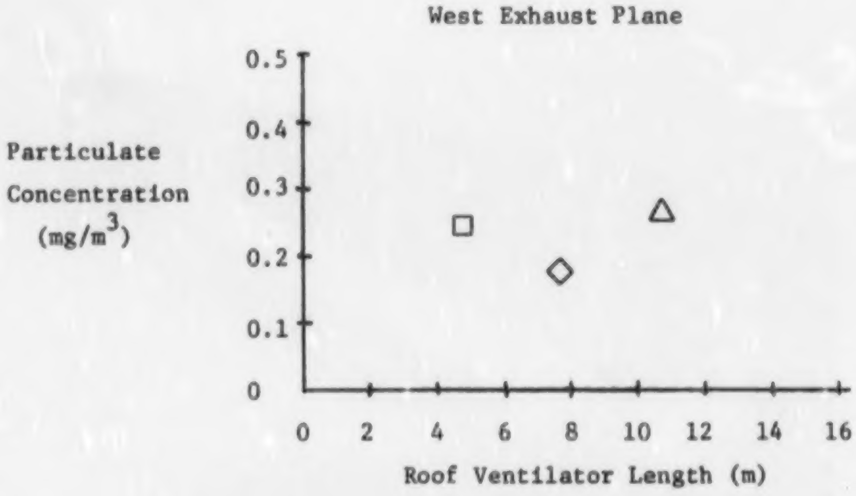


FIGURE 17

PRELIMINARY FIELD TEST CONCENTRATION MEASUREMENTS

HITCHCOCK INDUSTRIES ROOF VENTILATOR

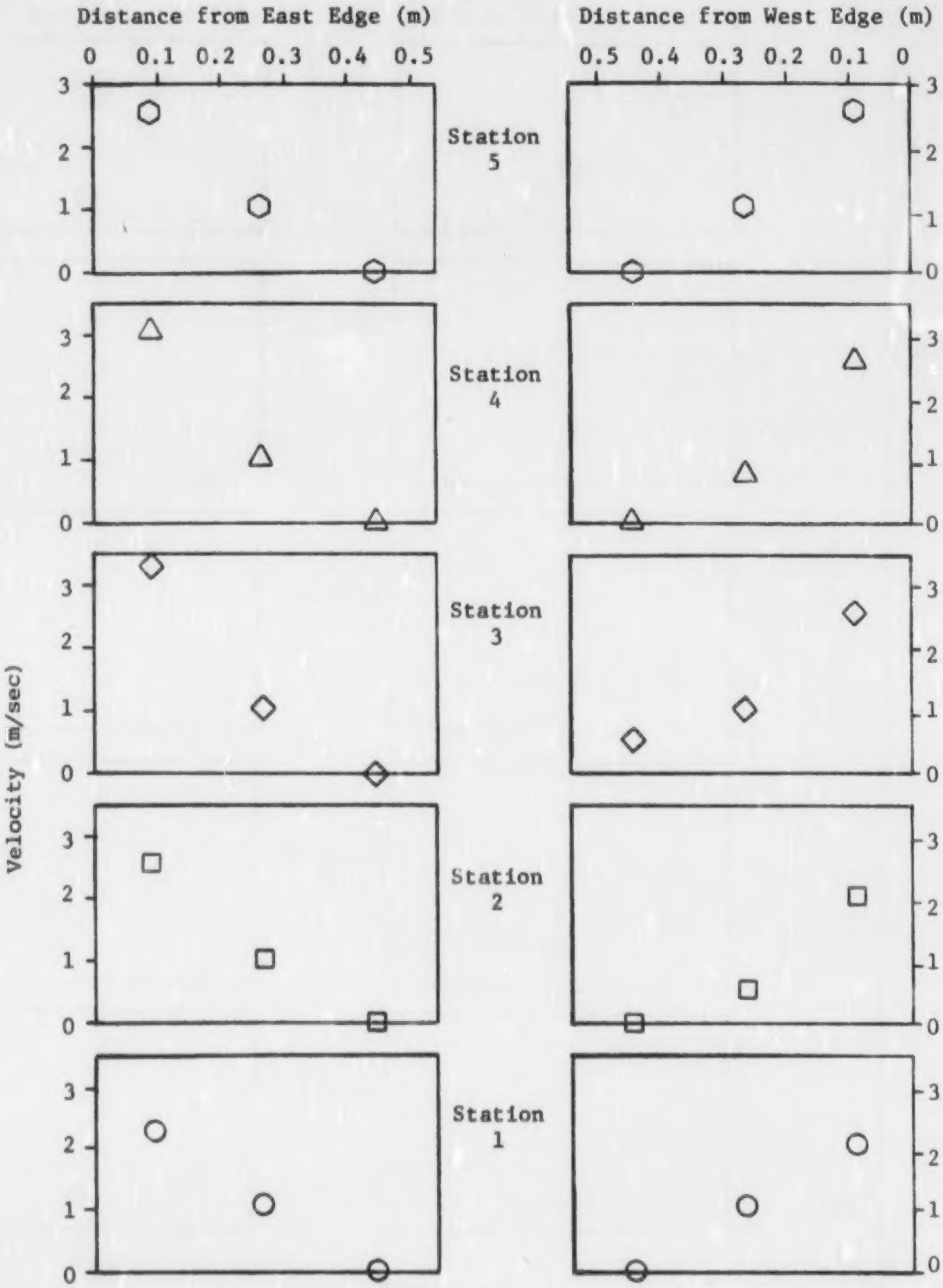


FIGURE 18

PRELIMINARY FIELD TEST VELOCITY SURVEY 1,
HITCHCOCK INDUSTRIES ROOF VENTILATOR

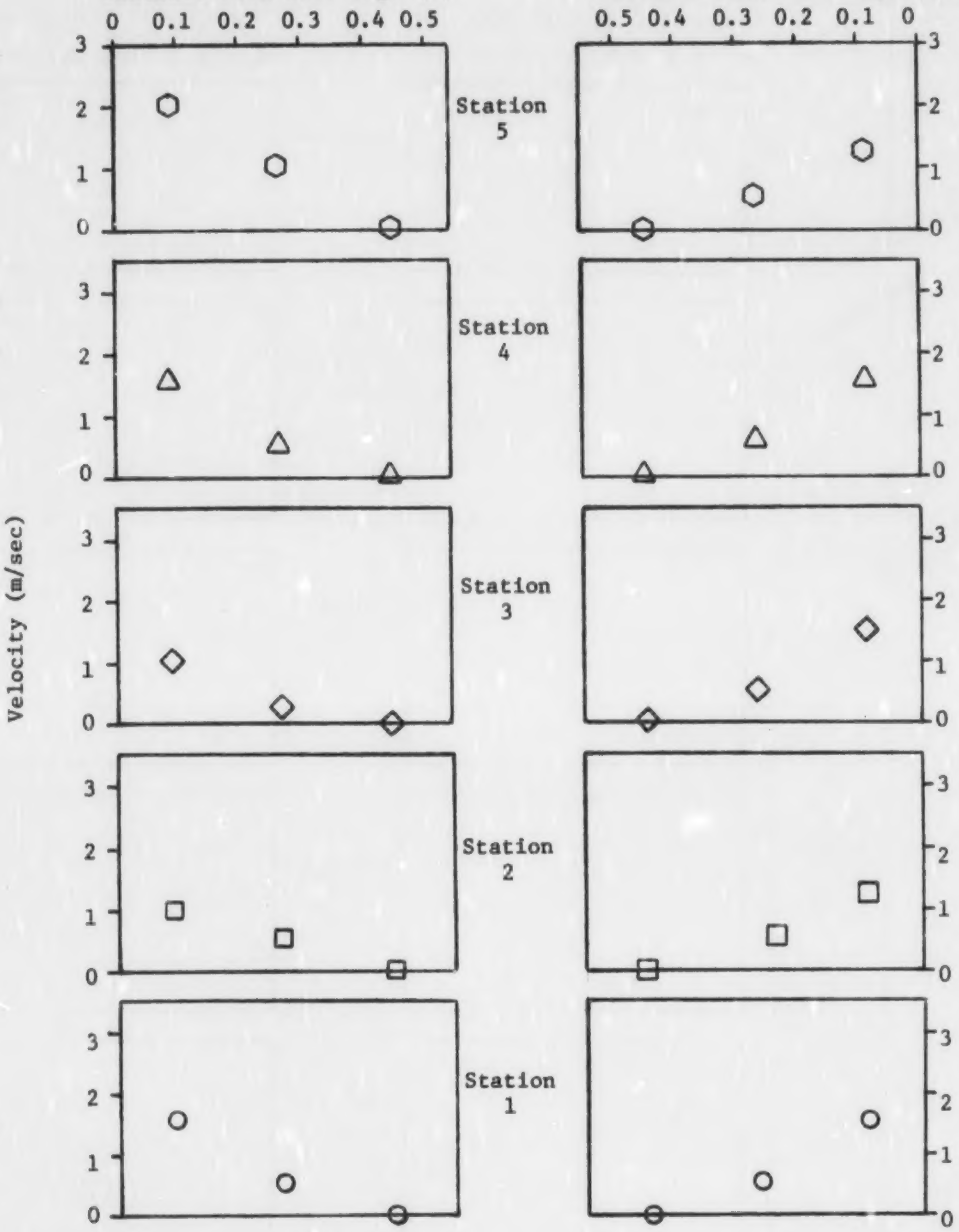


FIGURE 19

PRELIMINARY FIELD TEST VELOCITY SURVEY 2

HITCHCOCK INDUSTRIES ROOF VENTILATOR

The exhaust stream temperature was also found to vary considerably, ranging from 26°C to 49°C, the average temperature being approximately 34°C. The temperature was seen to vary with time and with position along the roof ventilator, although no attempt at correlation was made.

C. Model Studies

The model studies phase of the test program was developed on the basis of these preliminary observations and measurements. A laboratory model representative of a typical roof ventilator was designed and fabricated, and this model was used to evaluate techniques and instrumentation for use in roof ventilator emission measurement.

1. Model Design and Fabrication

Manufacturer's literature (Ref. 34), and dimensional measurements taken at the Hitchcock site were used to fabricate a model of a section of roof ventilator (Fig. 20). This roof ventilator model was attached to a test section and connected to an existing duct network, used in a previous FluiDyne study at the firm's Rosemount Energy Conversion Laboratory. The model was oriented on the roof in such a way as to maximize the effect of the prevailing wind. The model test facility is shown schematically in Fig. 21 and the roof ventilator model atop the Energy Conversion Laboratory is illustrated in Fig. 22.

In order to provide the capability of introducing particulate matter into the model exhaust, an aerosol generation system was added to the existing ductwork (Fig. 23). The concept of the aerosol generation system was to atomize a weak saline solution by means of a spray nozzle. The heated air then induced evaporation of the water, leaving small particles of salt suspended in the flow stream.

Unfortunately, during the course of the test program with the roof ventilator model, FluiDyne's Energy Conversion Laboratory facility was destroyed by a fire, as was the entire roof ventilator test facility. This necessitated the construction of a second model at FluiDyne's Medicine Lake Aerodynamic Testing Laboratory. This model, illustrated in Figs. 24 and 25, followed essentially the same design as the original roof ventilator model. The aerosol generation system for the second roof ventilator model, illustrated in Fig. 26, also followed the same concept as in the original model facility.

Four sample ports were located at the base of the second roof model (Fig. 27) for evaluation of a second sampling plane in addition to the ventilator exhaust. Testing on both roof ventilator models included flow visualization studies, velocity measurements, and particulate concentration measurements.

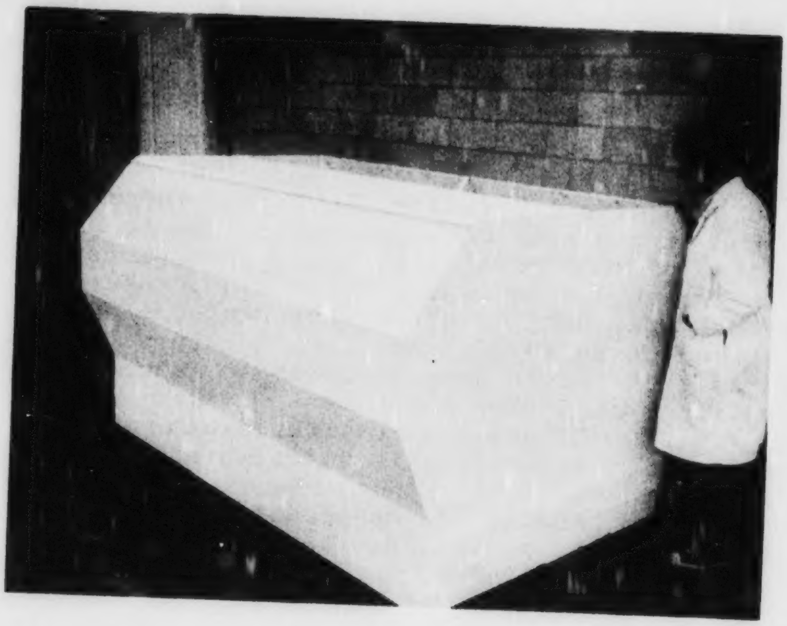


FIGURE 20. ROOF VENTILATOR MODEL

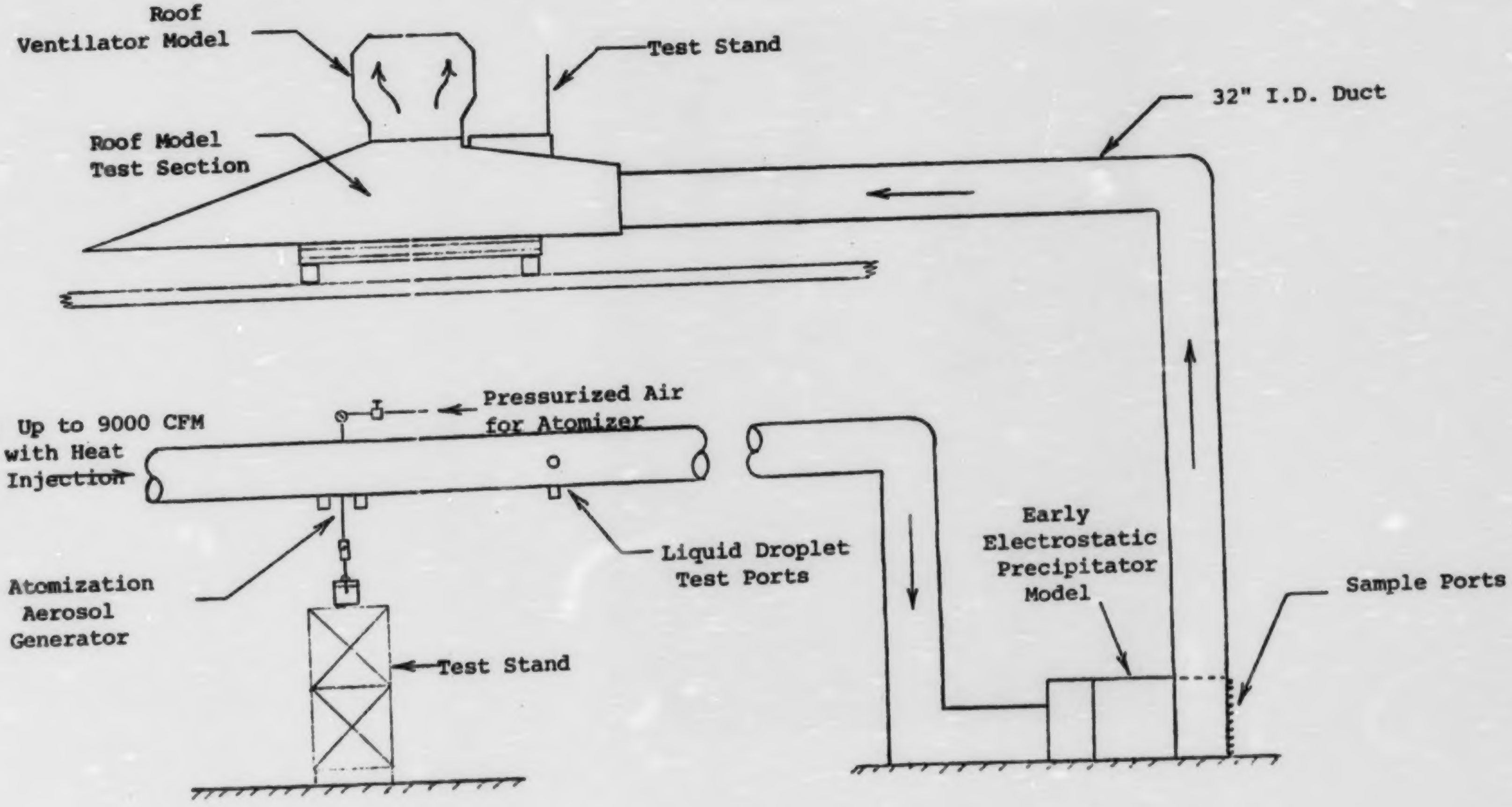

Roof Ventilator Model
Test Stand
32" I.D. Duct
Roof Model Test Section
Pressurized Air for Atomizer
Up to 9000 CFM with Heat Injection
Liquid Droplet Test Ports
Early Electrostatic Precipitator Model
Sample Ports
Atomization Aerosol Generator
Test Stand

FIGURE 21. ROOF VENTILATOR MODEL TEST FACILITY — ROSEMOUNT ENERGY CONVERSION LABORATORY

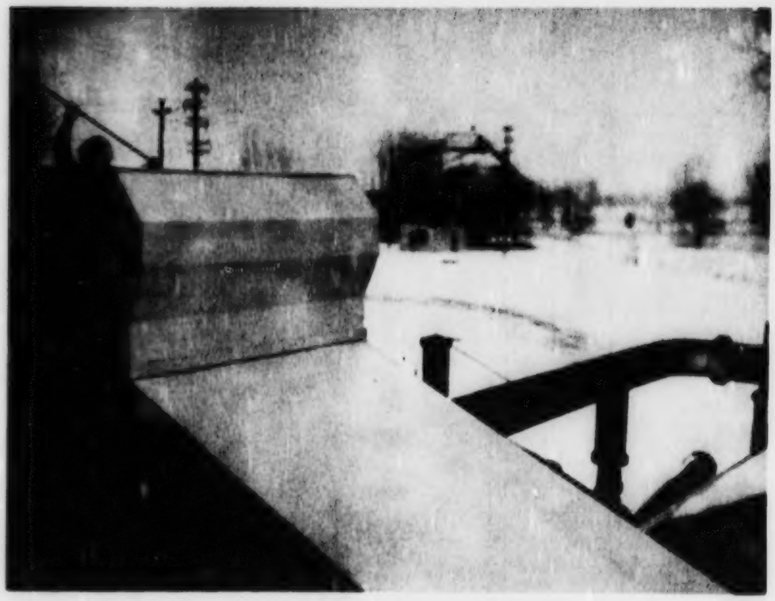


FIGURE 22. ROOF VENTILATOR MODEL TEST SECTION

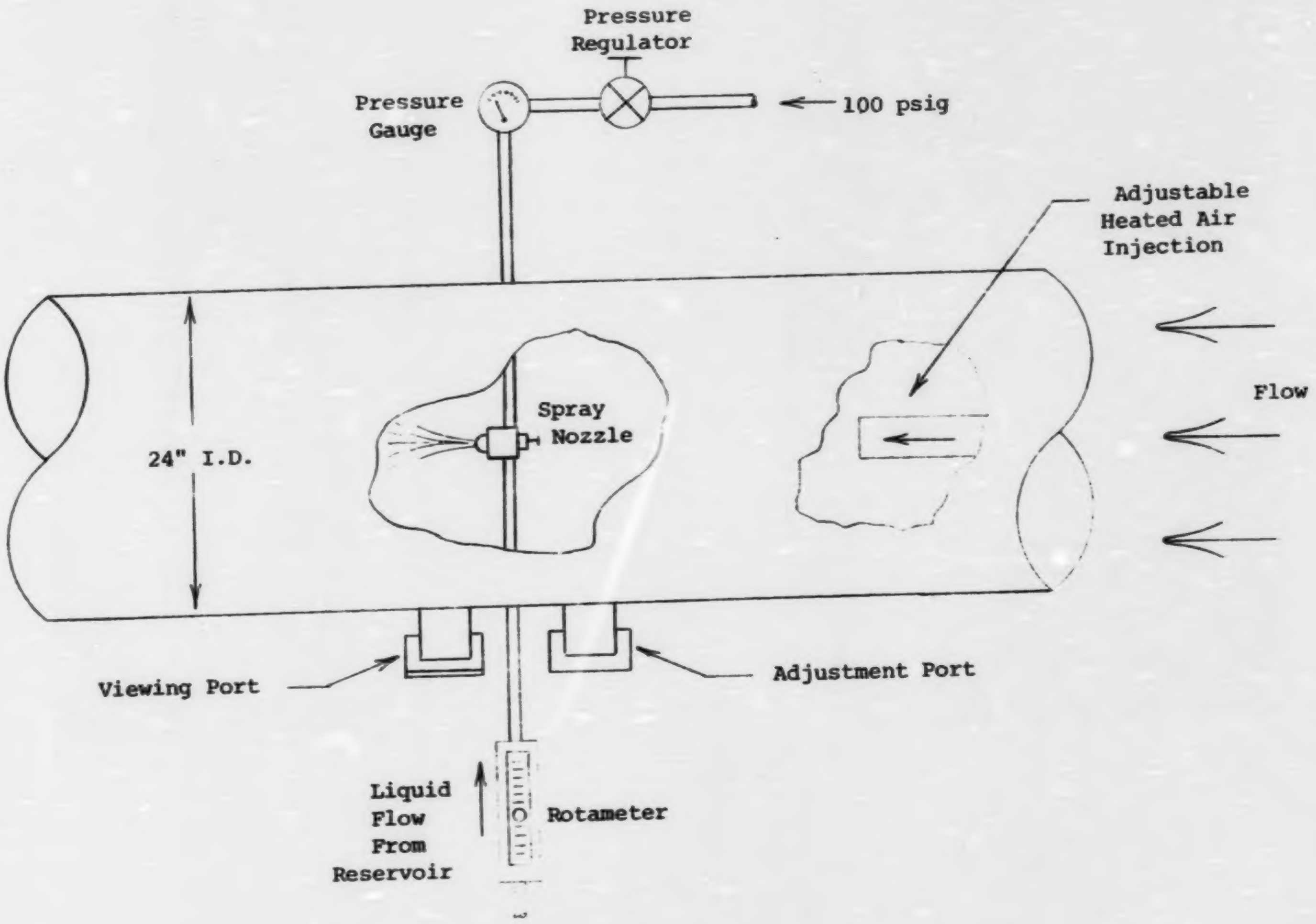

Pressure Regulator
Pressure Gauge
100 psig
Adjustable Heated Air Injection
Flow
Spray Nozzle
24" I.D.
Viewing Port
Adjustment Port
Liquid Flow From Reservoir
Rotameter

FIGURE 23. ATOMIZATION AEROSOL GENERATOR AND HOT AIR INJECTION SYSTEM — ROSEMOUNT ENERGY CONVERSION LABORATORY

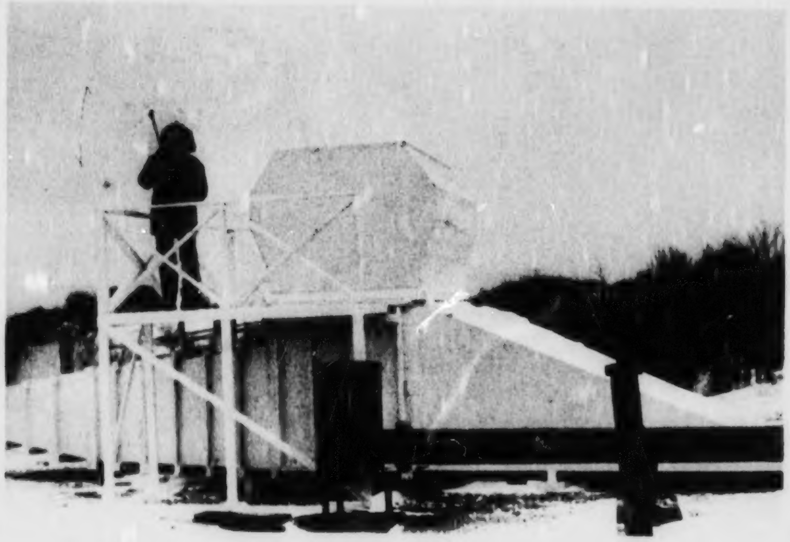


FIGURE 24. ROOF VENTILATOR MODEL AT MEDICINE LAKE AERODYNAMIC TEST FACILITY - VIEWED FROM NORTH

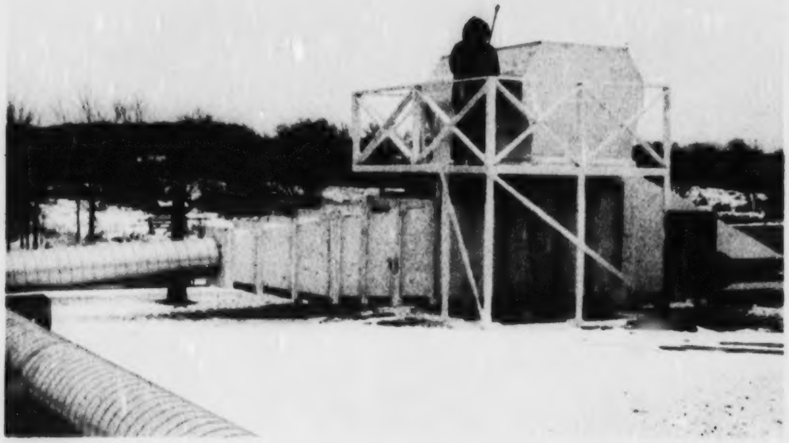
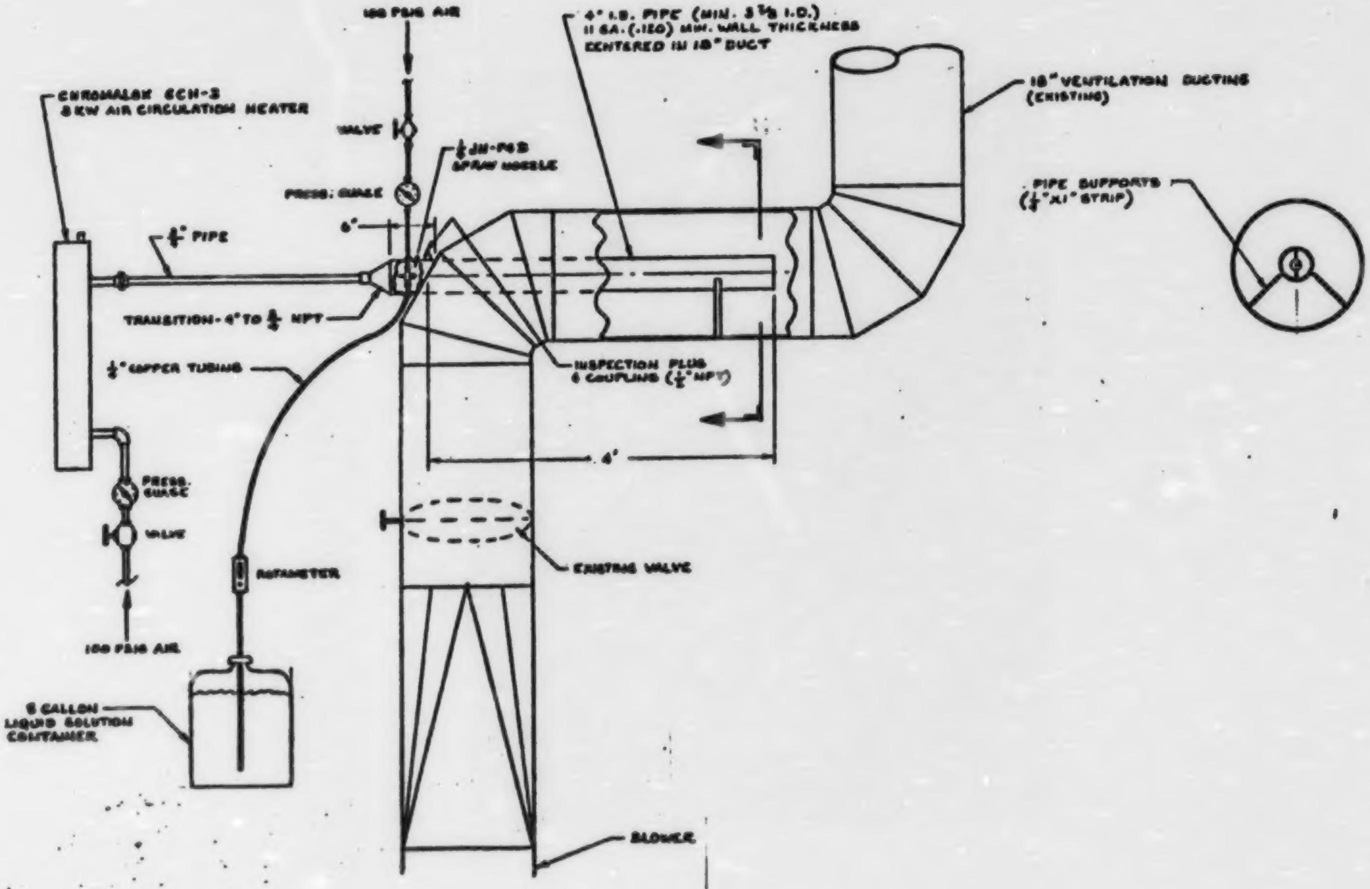


FIGURE 25. ROOF VENTILATOR MODEL AND DUCTING AT MEDICINE LAKE AERODYNAMIC TEST FACILITY - VIEWED FROM NORTHEAST



100 PSIG AIR
4" I.D. PIPE (MIN. 3⅞ I.D.)
11 GA. (.120) MIN. WALL THICKNESS
CENTERED IN 18" DUCT
CHROMALOX ECH-3
3 KW AIR CIRCULATION HEATER
18" VENTILATION DUCTING
(EXISTING)
VALVE
½ JN-F63
SPRAY NOZZLE
PRESS. GUAGE
6"
½" PIPE
PIPE SUPPORTS
(½"X1" STRIP)
TRANSITION - 4" TO ½ NPT
½" COPPER TUBING
INSPECTION PLUG
& COUPLING (½" NPT)
4'
PRESS. GUAGE
VALVE
ROTAMETER
EXISTING VALVE
100 PSIG AIR
5 GALLON
LIQUID SOLUTION
CONTAINER
BLOWER

FIGURE 26. ATOMIZATION AEROSOL GENERATOR SYSTEM WITH HOT AIR INJECTION - MEDICINE LAKE AERODYNAMIC TEST FACILITY

FIGURE 27. ROOF VENTILATOR MODEL SAMPLE PORTS - VIEWED FROM NORTHEAST

2. Flow Velocity Studies

The first objective of the model testing program was to evaluate the capability to determine total volumetric flow through the roof model. Early observations indicated that the exhaust from the roof ventilator model often exhibited very complex flow patterns which could not be readily determined with conventional velocity instrumentation. Therefore, flow visualization studies were conducted using lightweight flow direction tufts as well as smoke injection studies to examine the fluid motion through the roof ventilator (Figs. 28 and 29).

A circulatory flow pattern, illustrated schematically in Fig. 30, was observed at the ventilator exhaust. The severity of the exit velocity profile as well as the depth in the roof ventilator to which circulatory flow was evident were seen to depend strongly on the atmospheric wind conditions. This fact, together with the inability of conventional velocity instrumentation to give reliable values for total volumetric flow rate, led to the conclusion that velocity measurements should be made in a plane other than the exit from the ventilator.

A plane near the base of the roof ventilator was felt to provide a better sampling location. The sample ports shown in Fig. 27 were used to study the flow behavior near the base of the roof model. A certain degree of circulatory flow was still evident, but appeared to be of a steady state nature, unaffected by wind gusts and other external disturbances. It was determined that this circulatory flow was caused by the rapid expansion of the test section which supplied the flow to the roof model (see Figs. 24 and 25) and that insertion of a flow straightening baffle upstream of the roof model eliminated this circulatory flow near the base of the model. A typical flow profile observed with this flow straightening baffle in place is illustrated in Fig. 31. A useful feature of this baffle was the capability to produce circulatory flow or uniform flow at the base of the model for the purpose of evaluating the usefulness of various velocity instruments.

Having established the basic characteristics of the flow through the roof ventilator model, the remaining task was to evaluate the suitability of various commercially available instruments for measurement of the volumetric flow rate. A large number of instruments were considered for this application, and their suitability was evaluated through extensive testing both in the roof ventilator model and at the Hitchcock Industries site. A detailed description of this evaluation program is given in the Appendix. The description of this program was arranged in the form of a self-contained dissertation entitled "Velocity Instrumentation for Low Velocity, Partially Confined Source Particulate Sampling" due to the general importance and usefulness of this material with regard to the problems of atypical emission sources. To summarize the results of the

FIGURE 28. FLOW DIRECTION INDICATING TUFTS IN ROOF VENTILATOR MODEL EXHAUST

FIGURE 29. SMOKE GENERATOR FLOW INDICATOR IN ROOF VENTILATOR MODEL EXHAUST

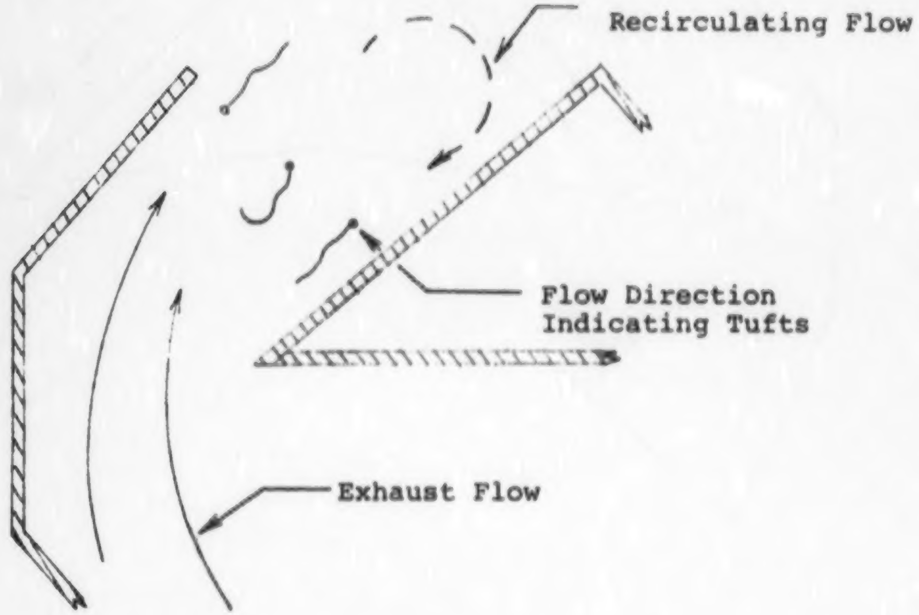

Recirculating Flow
Flow Direction
Indicating Tufts
Exhaust Flow

FIGURE 30. SCHEMATIC OF OBSERVED FLOW
(END VIEW OF ROOF MODEL)

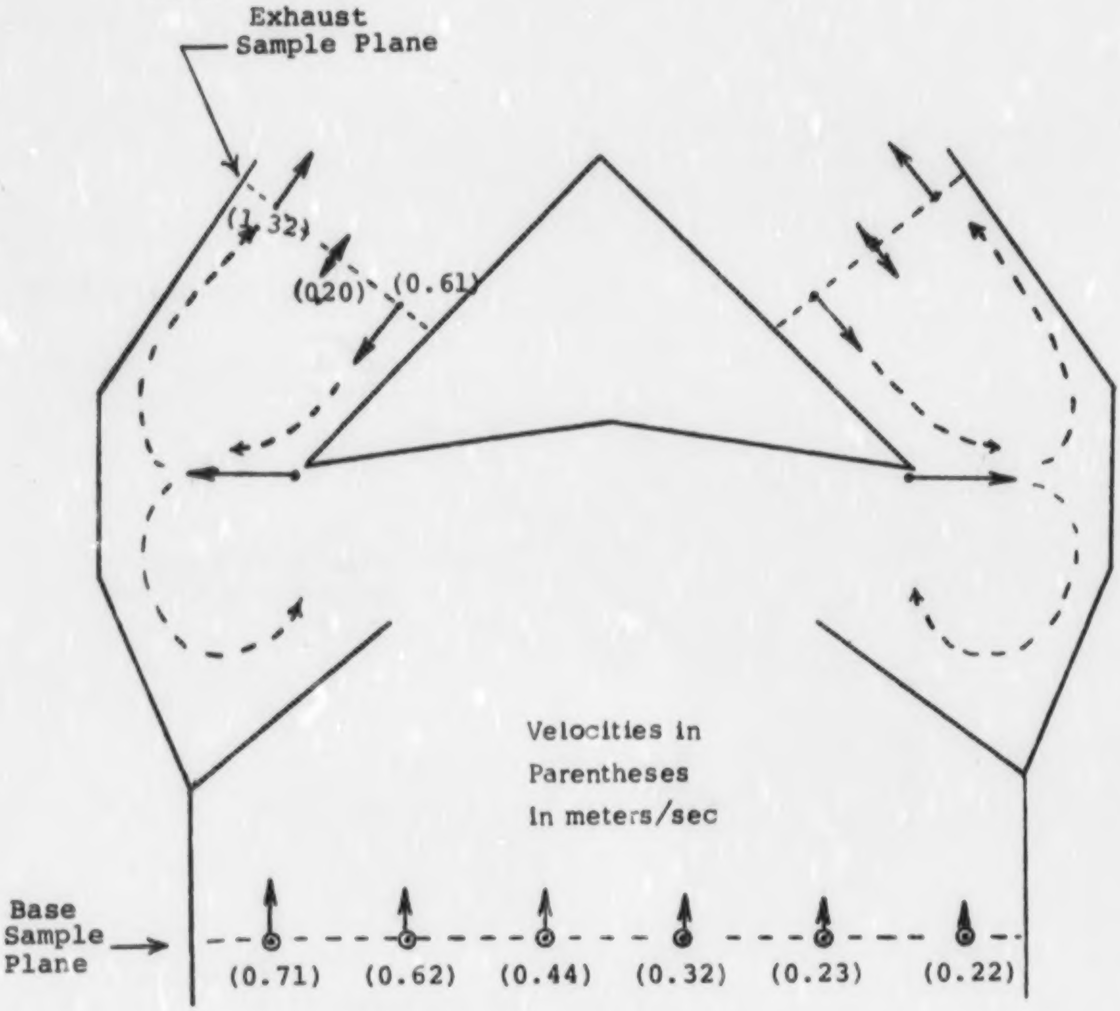

Exhaust
Sample Plane
(1.32)
(0.20)
(0.61)
Velocities in
Parentheses
in meters/sec
Base
Sample
Plane
(0.71)
(0.62)
(0.44)
(0.32)
(0.23)
(0.22)

FIGURE 31. TYPICAL FLOW VELOCITIES AT VARIOUS POINTS IN ROOF VENTILATOR MODEL

investigation into velocity instrumentation, it was found that a heated thermopile anemometer, the Hastings-Raydist PCI-30, was capable of accurate determination of the total volumetric flow rate when used at the base sampling plane under two conditions: 1) when the uniform flow baffle was used to provide a non-circulatory flow pattern, and 2) when a secondary observation tool, a lightweight flow direction indicator, was used in conjunction with the instrument in a circulatory flow field with the baffle absent. These results are indicated in Fig. 32. None of the velocity instruments evaluated were capable of providing accurate flow rate data when used at the exhaust plane of the roof ventilator model.

3. Particulate Concentration Studies

The reliability of particulate concentration measurements using the high volume sampler (Fig. 12) was also evaluated through roof ventilator model studies. The procedure utilized for this evaluation was to induce particulate into the model ductwork by means of the aerosol generation system and attempt to measure the particulate concentration at the roof ventilator model exhaust or at the base of the roof model through the sample ports. The actual concentration was monitored in the ductwork upstream of the roof ventilator model using EPA Method 5 sampling techniques, collecting particulate on 47 mm Gelman Type A glass fiber filters.

The results of these measurements are shown in Fig. 33. The measurements at the exhaust plane consist of an average of several measurements at different points, while those at the base plane represent measurement at a single point near the center of the roof ventilator model. A great variety of atmospheric conditions was encountered in the course of the particulate concentration testing. Isokinetic sampling with the high volume sample probe was rarely achieved. Sampling rates were typically in the range of 150% to 250% of the isokinetic rate. No obvious correlation was seen between sampling rate or atmospheric conditions and degree of accuracy of the results.

The measured particulate concentration is generally seen from Fig. 33 to agree rather poorly with the actual values. However, an overall reliability of ± 25% is indicated over a large range of particulate concentrations for samples taken at the base of the roof ventilator model. In all but one test, the measurements at the base plane indicate a higher than actual concentration. At very low concentrations, on the order of those observed in the preliminary field tests, accuracy is seen to be as poor as +77% in one case. The disagreement may be exaggerated, however, due to the small weight changes of the standard filters at these low concentration levels.

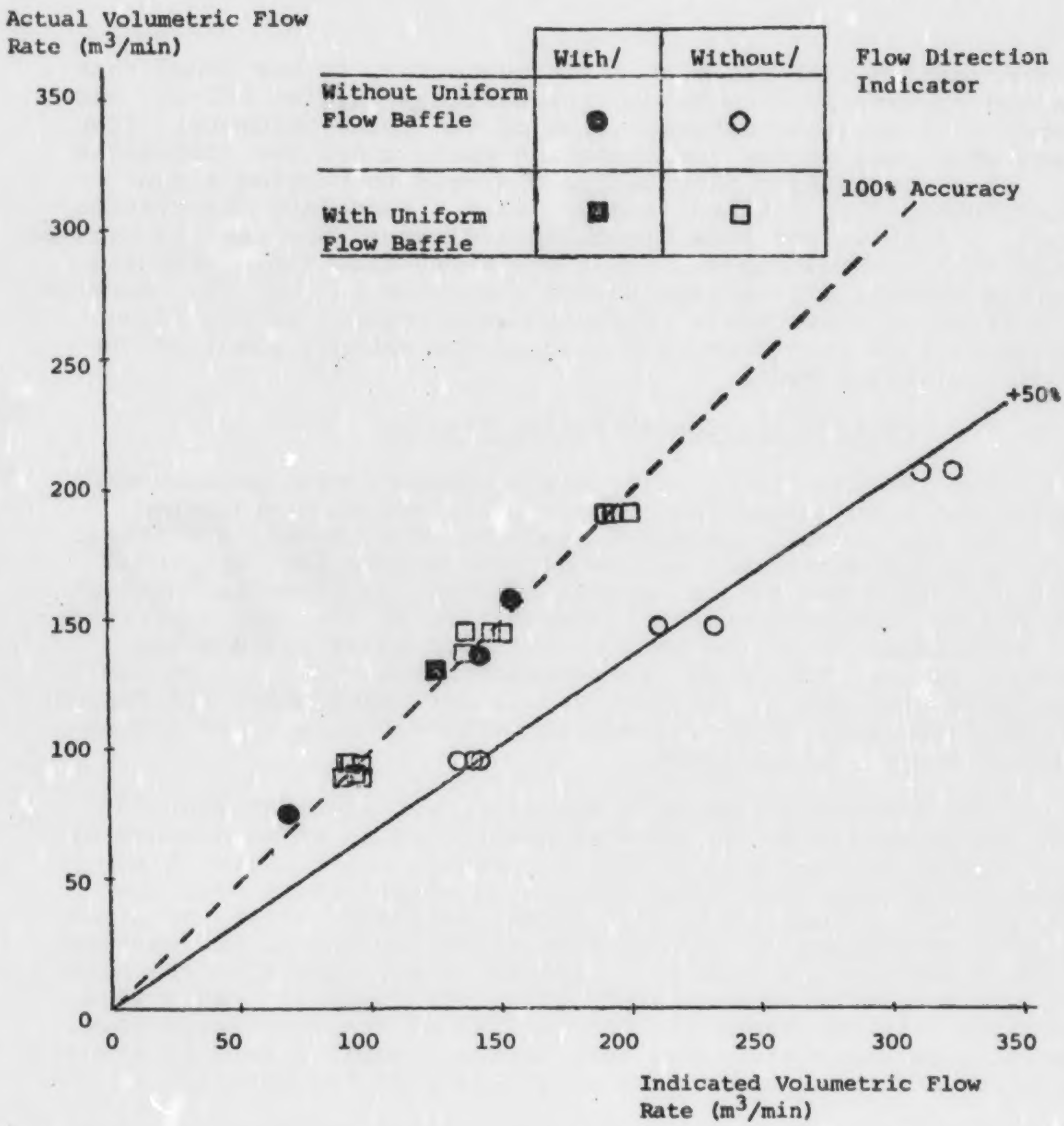


FIGURE 32. VOLUMETRIC FLOW RATE AT BASE OF ROOF VENTILATOR MODEL DETERMINED WITH HASTINGS-RAYDIST PCI-30 HOT THERMOPILE ANEMOMETER

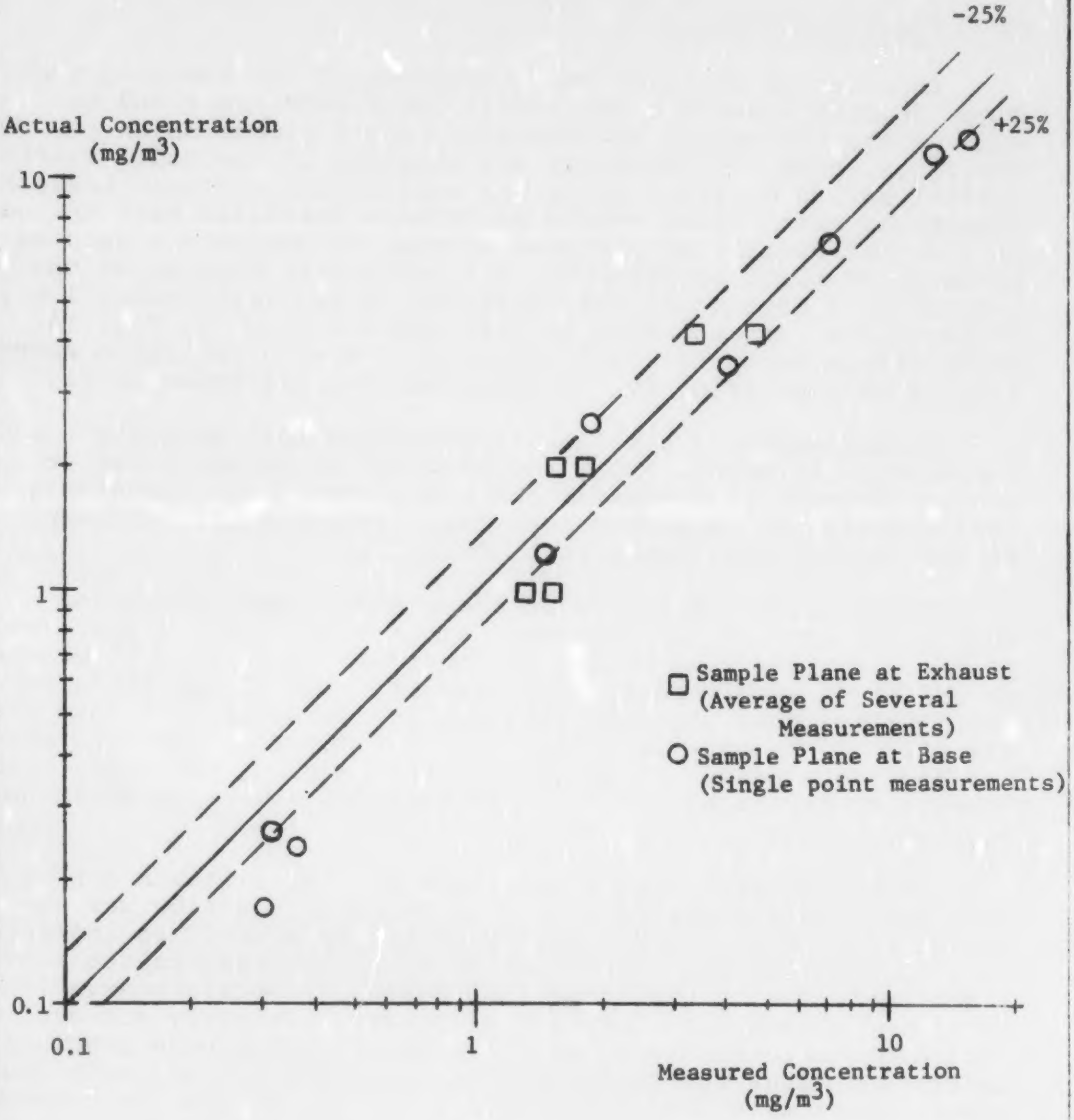


FIGURE 33

PARTICULATE CONCENTRATION MEASUREMENT IN
ROOF VENTILATOR MODEL

In general, the high volume sampler method used in a sampling plane at the base of the roof ventilator model gave conservatively higher particulate concentration results regardless of sampling rate. Further evaluation of the sampling techniques was precluded by time and budget limitations, due in part to difficulties in operation of the aerosol generation system. Additional study at a future time would be desirable in order to more precisely evaluate the reliability of the method.

D. Final Field Tests

In order to evaluate the usefulness of the sampling technique described above under actual field conditions and to examine the effects of the extended length dimension on the roof ventilator problem, which was not possible in the model studies, a final series of field tests was carried out at the Hitchcock Industries site. Five sample ports were installed near the base of the roof ventilator pictured in Fig. 10 during a scheduled shutdown of plant activities. The ports were located at the midpoints of five equal area sections of the ventilator, i.e., at locations corresponding to Stations 1-5 shown in Fig. 14. These sample ports provided access to the more favorable sampling plane identified by the model studies, as shown in Fig. 34.

Measurements of particulate concentration, velocity, and temperature were made using the high volume sample probe, the heated thermopile anemometer and a calibrated iron-constantan thermocouple, all inserted into the roof ventilator effluent stream through the sample ports (Fig. 34).

Particulate concentration measurements were conducted throughout each day of testing. A total of five 1.5 hour samples (except one test which was concluded after only 45 minutes at the first sample port) were taken at each of the five sample ports in the hope that the data would provide insight into the timewise and lengthwise variations of particulate concentration and provide a basis for evaluating the sampling technique with respect to applicability to other extended dimension emission sources.

Velocity measurements were made at various times during each day. During all five days of testing, the flow was observed to be directed relatively uniformly upward, as indicated by a lightweight flow direction tuft, in contrast to the supposed occasional circulatory flow based on visual observations of rising plumes from inside the foundry. Velocity surveys including measurements at all five sample ports were possible before and after the concentration measurements, but only four sample ports were used for velocity surveys during the concentration measurements since the sample probe and velocity probe could not be inserted through the sample ports simultaneously.

FIGURE 34. PARTICULATE CONCENTRATION AND VELOCITY MEASUREMENTS AT BASE OF HITCHCOCK INDUSTRIES ROOF VENTILATOR

The measurements made during the final field tests are summarized in Figs. 35 through 39. The average velocity at each sample port, determined from a six-point widthwise velocity survey, and the particulate concentration are plotted vs. the time of day at which each measurement was made. All five days of field testing are compressed onto a single scale, representing the normal work day, and each data point is identified as to the day it was taken.

Several observations can be made from the roof ventilator measurements shown in Figs. 35 through 39. The average velocity at a given sampling station often varied considerably with time on a given day and also varied from day to day at a given time. General trends can be seen, however. The curves shown on these Figures represent intuitive estimates of the "average" data and are not based on curve-fitting or regression formulas. It should be emphasized that the "point of average velocity" was not the same in all cases, as would be expected for flow in a pipe or duct, but was seen to vary over the entire width of the roof ventilator as the various velocity surveys were conducted.

The particulate concentration also varied during each day of testing. In general, concentration levels were seen to be higher near the midpoint of the roof ventilator than at the ends. Since the concentration measurements at each sample location were conducted on different days, it cannot be definitely determined that this variation is due to the position along the ventilator. However, observations of the foundry activities from day to day revealed no obvious procedural differences which would explain overall concentration variations of the magnitude observed in these measurements. Therefore, the observed variations of concentration with position in the roof ventilator are assumed to be indicative of the actual situation.

Investigations into a possible relationship between the effluent stream temperature and the velocity and/or concentration indicated no useful correlation. Since the flow through the roof ventilator is governed by a complex interaction of the inside temperature, outside temperature, wind conditions, and many other factors, this observation is not surprising. Often, higher temperatures accompanied higher velocities, but this was not always the case. The temperature occasionally appeared to vary cyclically over a period of several hours, but more often appeared quite random both with time and position, ranging between 35°C and 78°C over the five day test period. The average temperature was on the order of 55°C.

E. Evaluation of Sampling Technique

The information obtained during the roof ventilator test program led to several conclusions concerning basic measurement

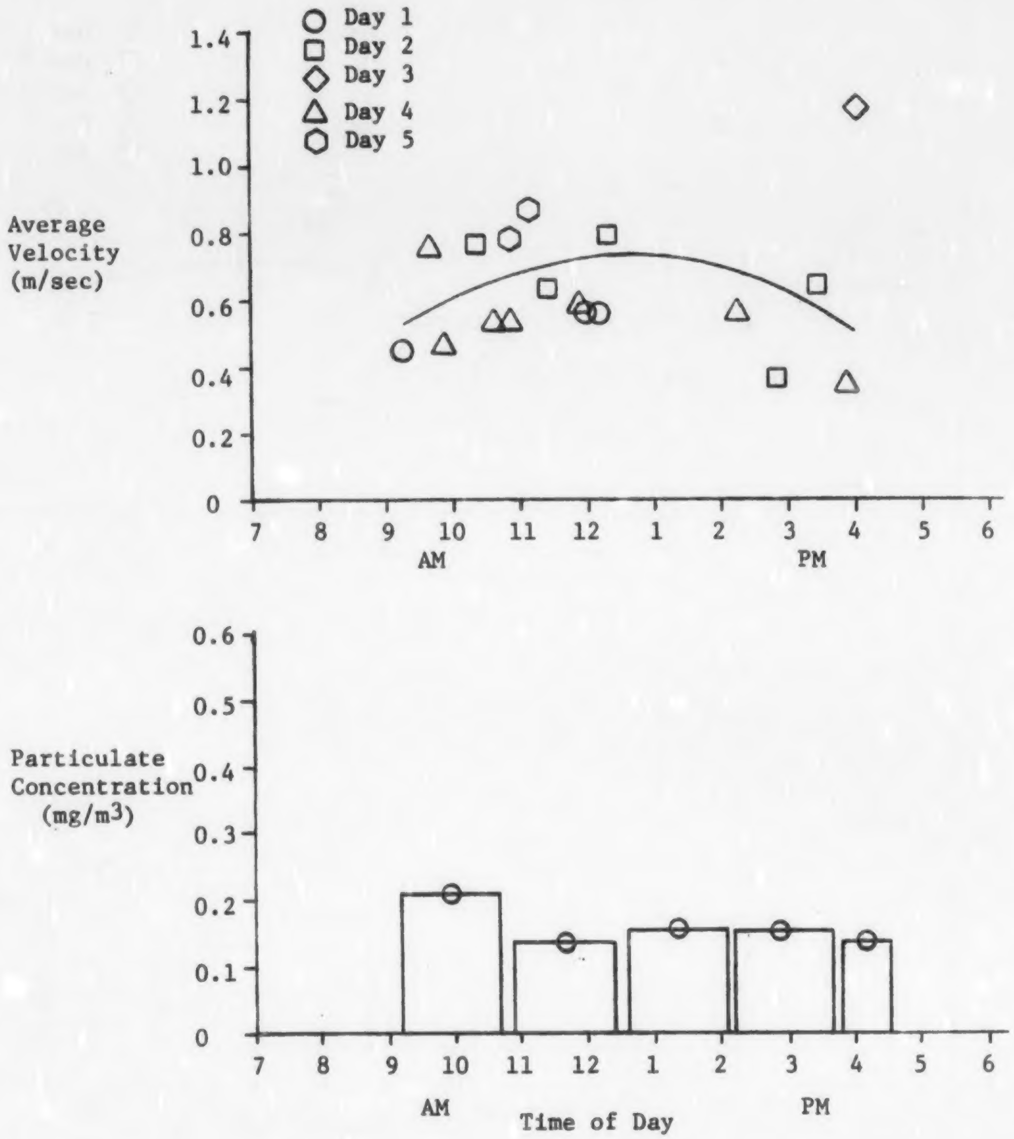


FIGURE 35

AVERAGE VELOCITY AND PARTICULATE CONCENTRATION

MEASUREMENTS - SAMPLE PORT 1

HITCHCOCK INDUSTRIES ROOF VENTILATOR

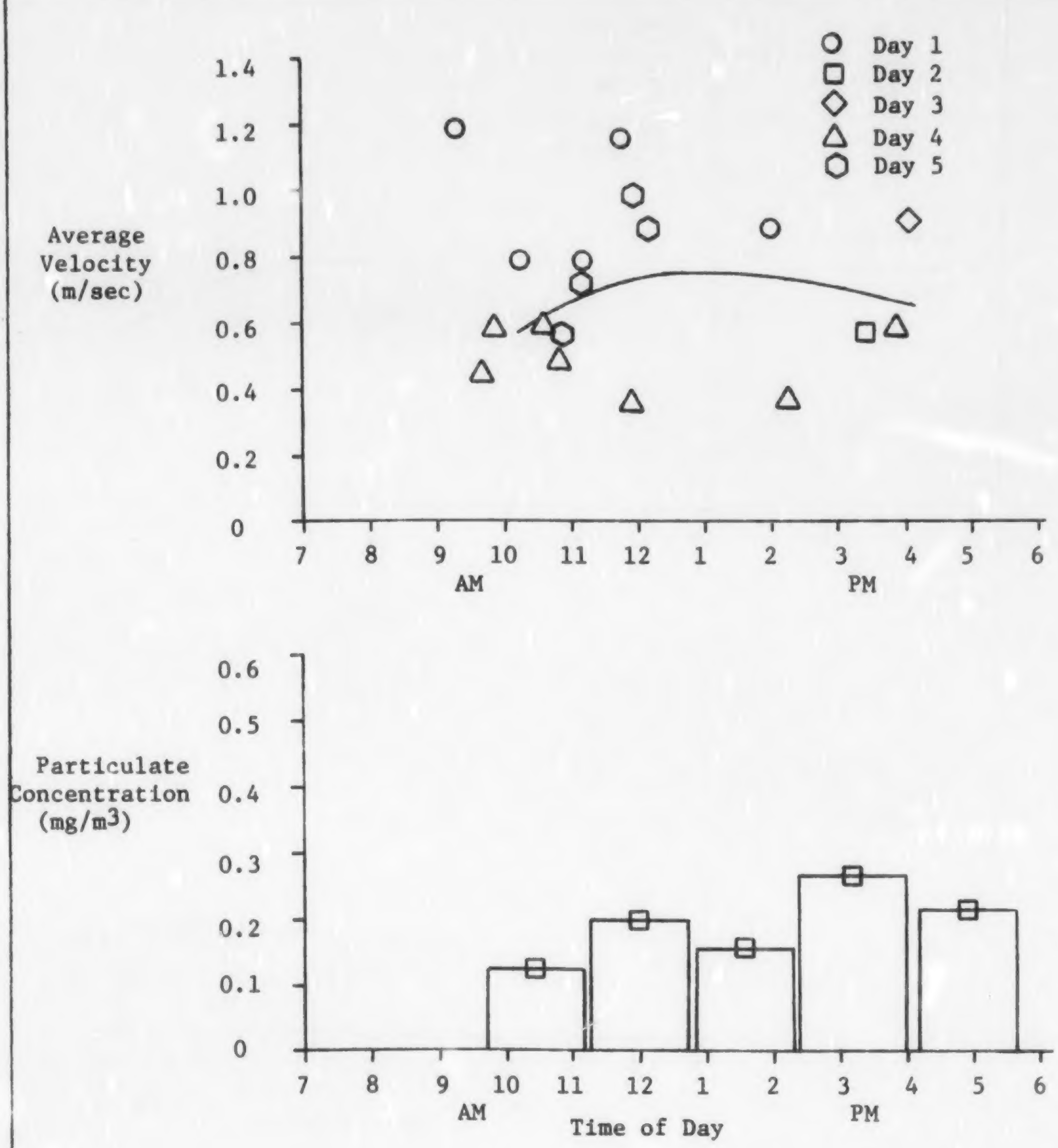


FIGURE 36

AVERAGE VELOCITY AND PARTICULATE CONCENTRATION

MEASUREMENTS - SAMPLE PORT 2

HITCHCOCK INDUSTRIES ROOF VENTILATOR

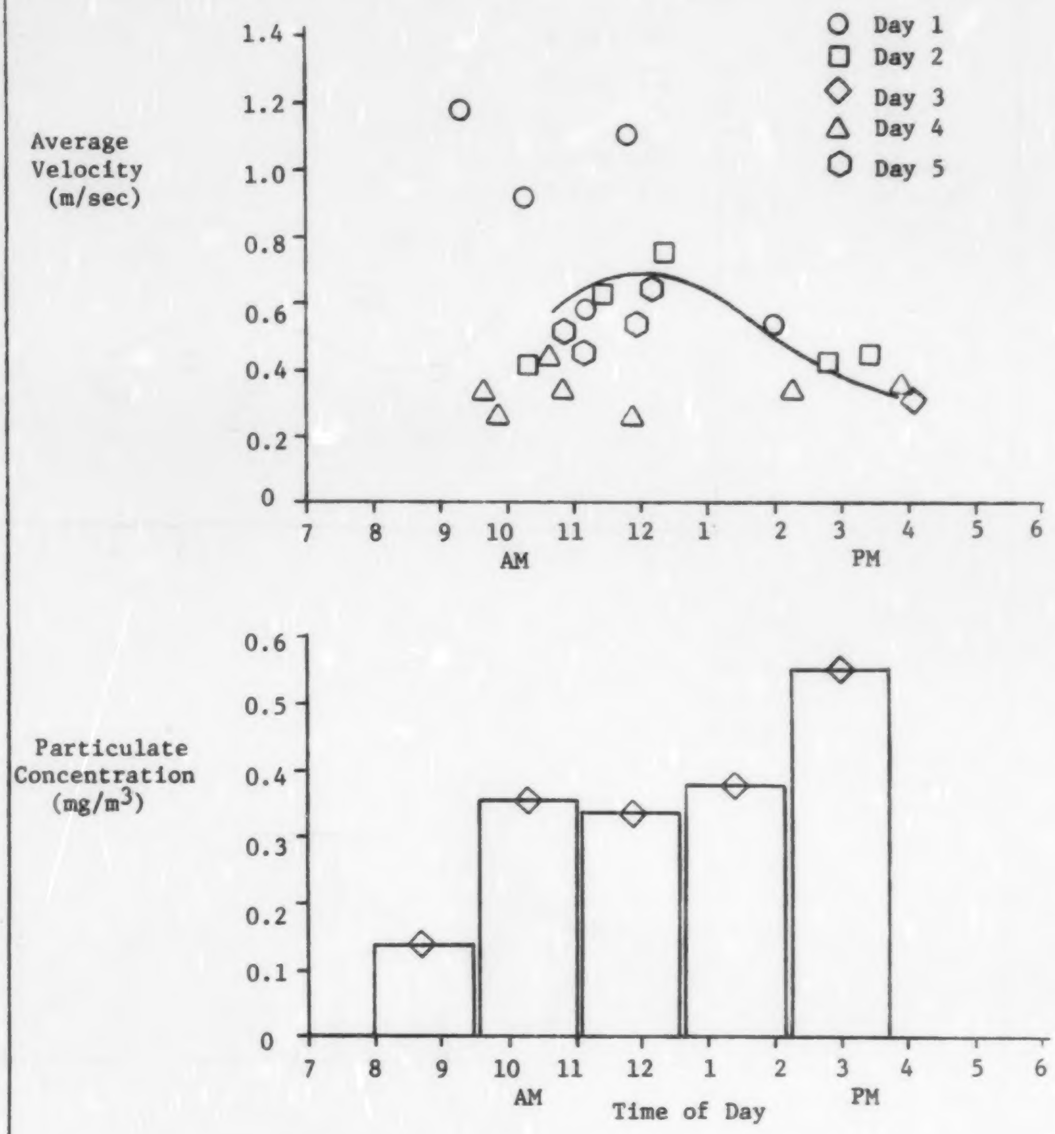


FIGURE 37

AVERAGE VELOCITY AND PARTICULATE CONCENTRATION

MEASUREMENTS - SAMPLE PORT 3

HITCHCOCK INDUSTRIES ROOF VENTILATOR

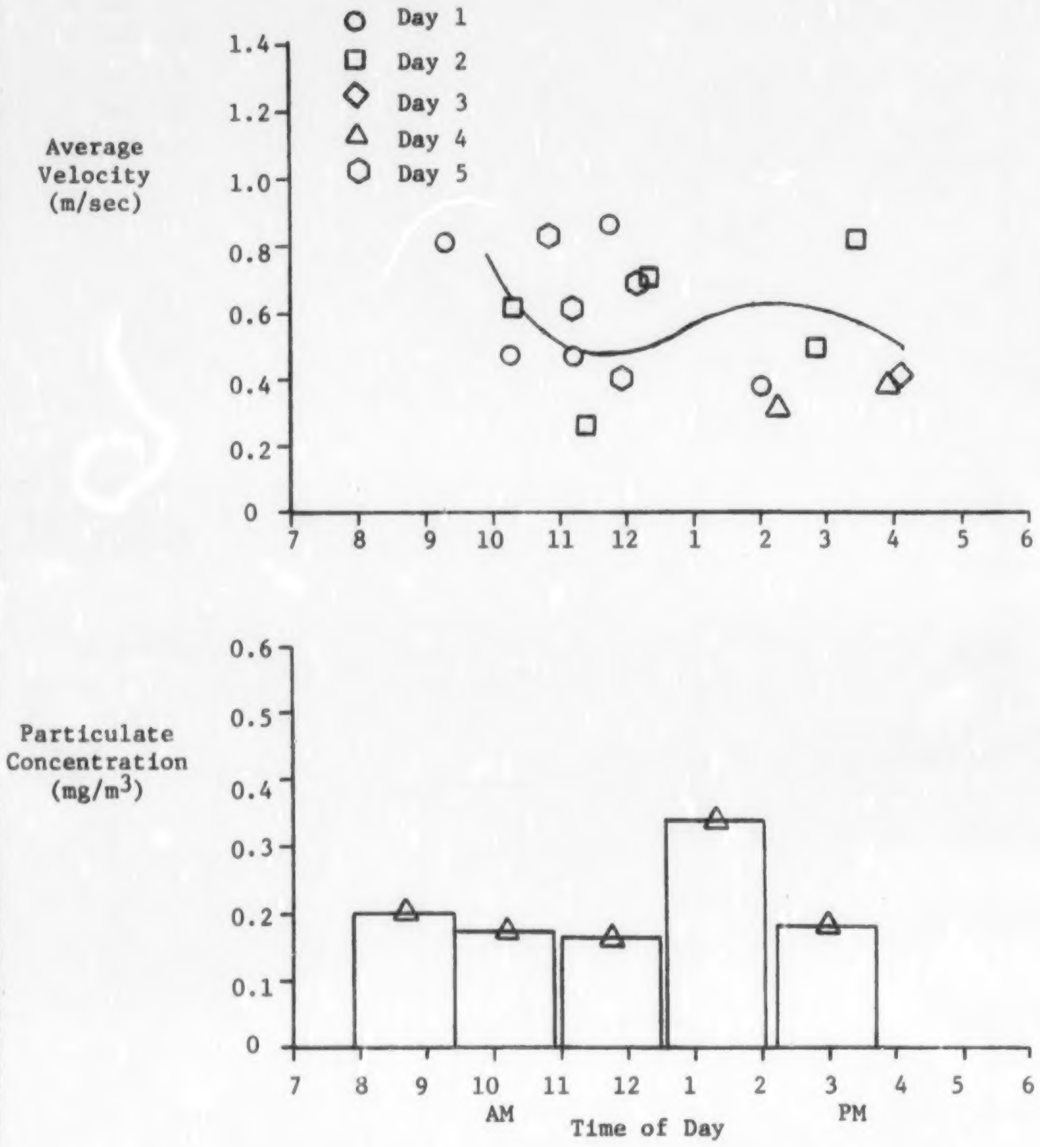


FIGURE 38

AVERAGE VELOCITY AND PARTICULATE CONCENTRATION

MEASUREMENTS - SAMPE PORT 4

HITCHCOCK INDUSTRIES ROOF VENTILATOR

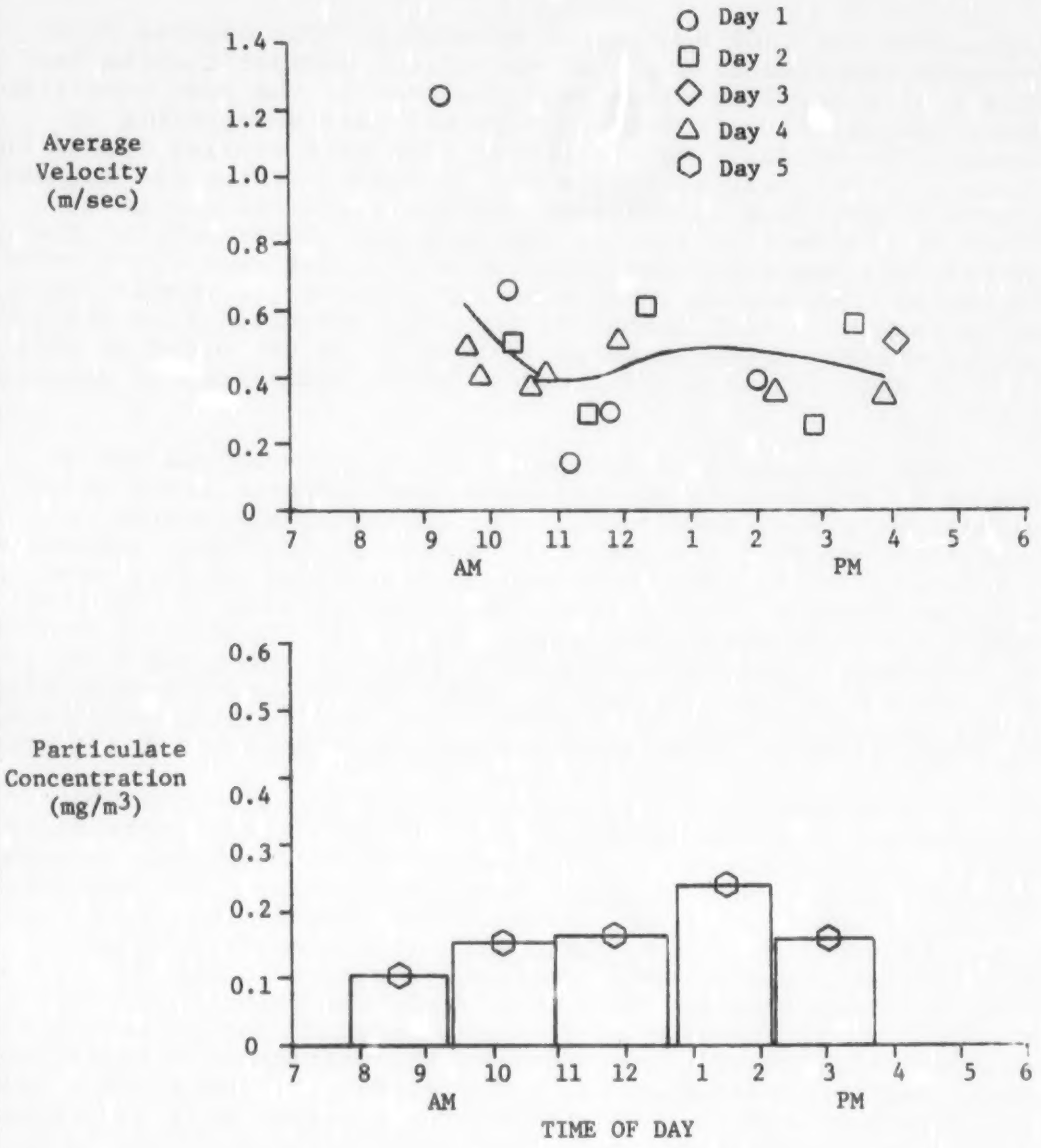


FIGURE 39

AVERAGE VELOCITY AND PARTICULATE CONCENTRATION

MEASUREMENTS - SAMPLE PORT 5

HITCHCOCK INDUSTRIES ROOF VENTILATOR

techniques for roof ventilator emissions. The complex flow patterns observed at the roof ventilator exhaust dictate the choice of a sampling plane near the base of the roof ventilator, where the velocity is more uniform and less susceptible to atmospheric winds. The volumetric flow rate studies showed that transverse velocity surveys with the heated thermopile anemometer provided very good indications (within ± 10%) of the total volumetric flow rate through the roof ventilator model. The particulate concentration studies in the roof ventilator model indicated that measurements with the high volume sample probe, while lacking a high degree of accuracy, provided reasonable, conservatively high estimates (typically on the order of +25% as seen in Fig. 33) of actual concentration regardless of sampling rate.

These observations defined a sampling technique and a degree of reliability for emission measurements in the model section of a roof ventilator. The questions which remained unanswered concern the number of sampling locations required for a given full-size roof ventilator. The choice of five sampling stations for the 15.24 m roof ventilator studied in the final field tests was based on a desire to obtain the maximum amount of information possible within the scope of the present project. For maximum reliability, particulate samples and velocity measurements should be obtained simultaneously and continuously at all sampling stations throughout the period of emission measurement.

A test program of this magnitude on a roof ventilator in the primary aluminum industry, for example, where ventilators may often be 200 m or more in length, would encounter serious problems with regard to economic feasibility. Thus, the number of sample stations required in a given application is of vital importance. The single application of a secondary aluminum foundry furnace room roof ventilator, studied under the present program, cannot be expected to provide the solution to this problem, since the type of flow and range of particulate concentration is heavily dependent on the particular activity which generates the emissions. In other words, the number of sample stations required for any specific application will undoubtedly depend on characteristics of that application and must be determined for each individual case.

The long sampling time required in order to obtain a weighable collection of particulate tends to preclude the use of widthwise particulate concentration traverses at each selected sampling station. Single point concentration measurements were, therefore, chosen on the basis of practicality. Widthwise velocity surveys, however, may be made with considerably less difficulty. In order to demonstrate the importance of the number of points chosen for a widthwise velocity survey, an example based on field test measurements was considered.

A typical velocity distribution, measured at approximately 3:30 p.m. on the second day of final field testing, was analyzed (see Fig. 40). The average velocity which would have been determined from 1, 2, 4, and 5 point widthwise surveys of the velocity distribution shown in Fig. 40 was computed at each sample station and compared with the average velocity from the 6 point surveys actually made during the field tests. The results of this comparison are shown in Table 10. For this particular velocity distribution, it can be seen that at least 4 or 5 point surveys are required to determine the average velocity at each station to within ± 10%. It must be emphasized that, while this velocity distribution is typical of those observed throughout the field test period, not only the average velocity but also the points of average velocity continuously varied with time as the basic velocity distribution varied with atmospheric conditions and activities within the foundry.

As an illustration of the importance of the number of sampling stations, a second example based on the final field test measurements may be of value. Consider a six-hour period, from 10:00 a.m. to 4:00 p.m., of emission from the 15.24 m roof ventilator. Based on the field test data, typical particulate concentration and average velocity profiles can be constructed as shown in Figs. 41 and 42 for three time instants during this six hour interval. It must be emphasized that these profiles were constructed from data taken over a five day period. The profiles shown in Figs. 41 and 42 are intended to represent a typical example only and should not be construed as actual emission measurements during a single six hour period.

The total emission during the six hour period was calculated following a number of simple methods. The basic emission calculation procedure followed the formula:

$$E = \sum_{i=1}^{N} \sum_{j=1}^{M} (C_j \overline{V}_j A_j) t_i$$

Where: E = total emission (gm)
C = particulate concentration (gm/m^3)
N = number of time increments
M = number of sample stations
$\overline{V}$ = average velocity (m/sec)
A = cross sectional area (m^2)
t = time interval (sec)

The first calculation was made assuming that the profiles shown in Figs. 41 a,b,c and 42 a,b,c each represented the average conditions for a two-hour period (41a and 42a represent the period from 10:00 a.m. to 12:00 p.m., etc.). Several emission calculations using various combinations of the data from Figs. 41 and 42 were then compared with the first calculation.

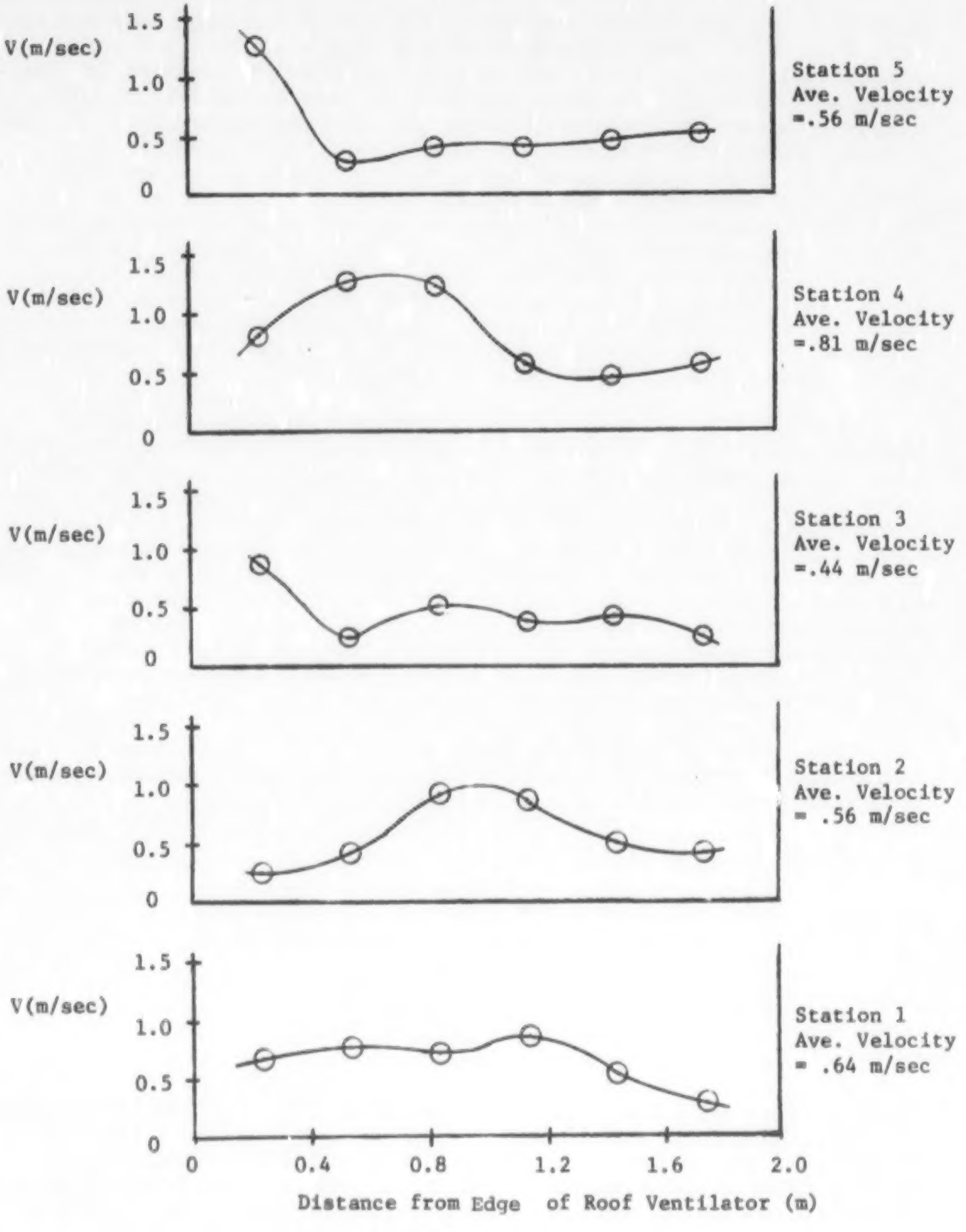


FIGURE 40

TYPICAL VELOCITY DISTRIBUTION AT BASE
OF HITCHCOCK INDUSTRIES ROOF VENTILATOR

TABLE 10

AVERAGE VELOCITY DETERMINED FROM WIDTHWISE VELOCITY SURVEYS, BASED ON FIG. 40

	No. of Points in Survey								
	1		2		4		5		6
Sample Station	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)	% Diff.	Avg. Vel. (m/sec)
1	.82	+28.1	.61	-4.7	.63	-2.3	.61	-5.0	.64
2	.97	+73.2	.39	-29.5	.55	-2.2	.53	-5.4	.56
3	.42	-4.5	.37	-17.0	.48	+8.0	.45	+2.7	.44
4	.93	+14.8	.85	+4.9	.79	-2.2	.80	-1.7	.81
5	.43	-23.2	.45	-20.5	.67	+19.2	.61	+8.2	.56

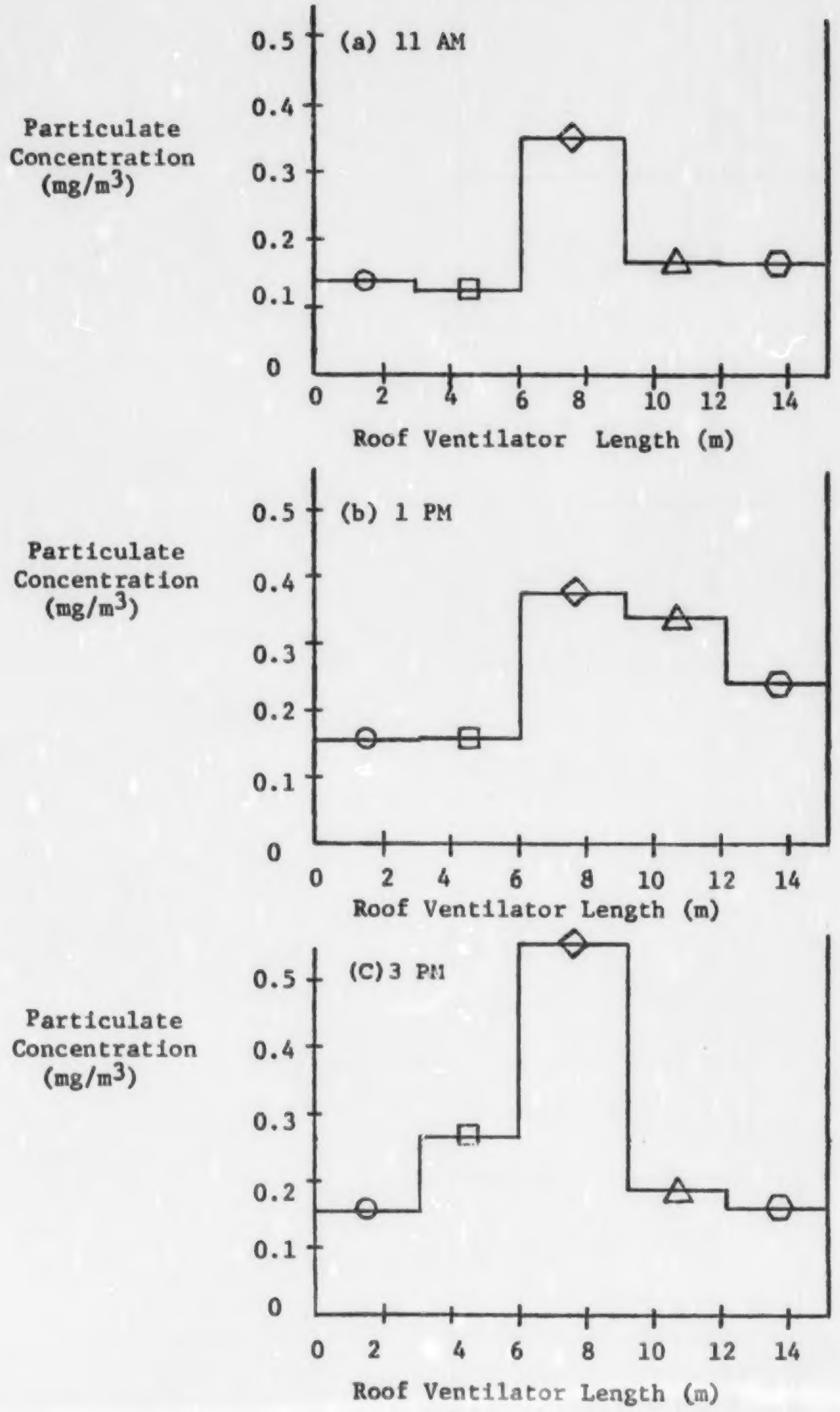


FIGURE 41

PARTICULATE CONCENTRATION PROFILES
FOR ROOF VENTILATOR EMISSION EXAMPLE PROBLEM

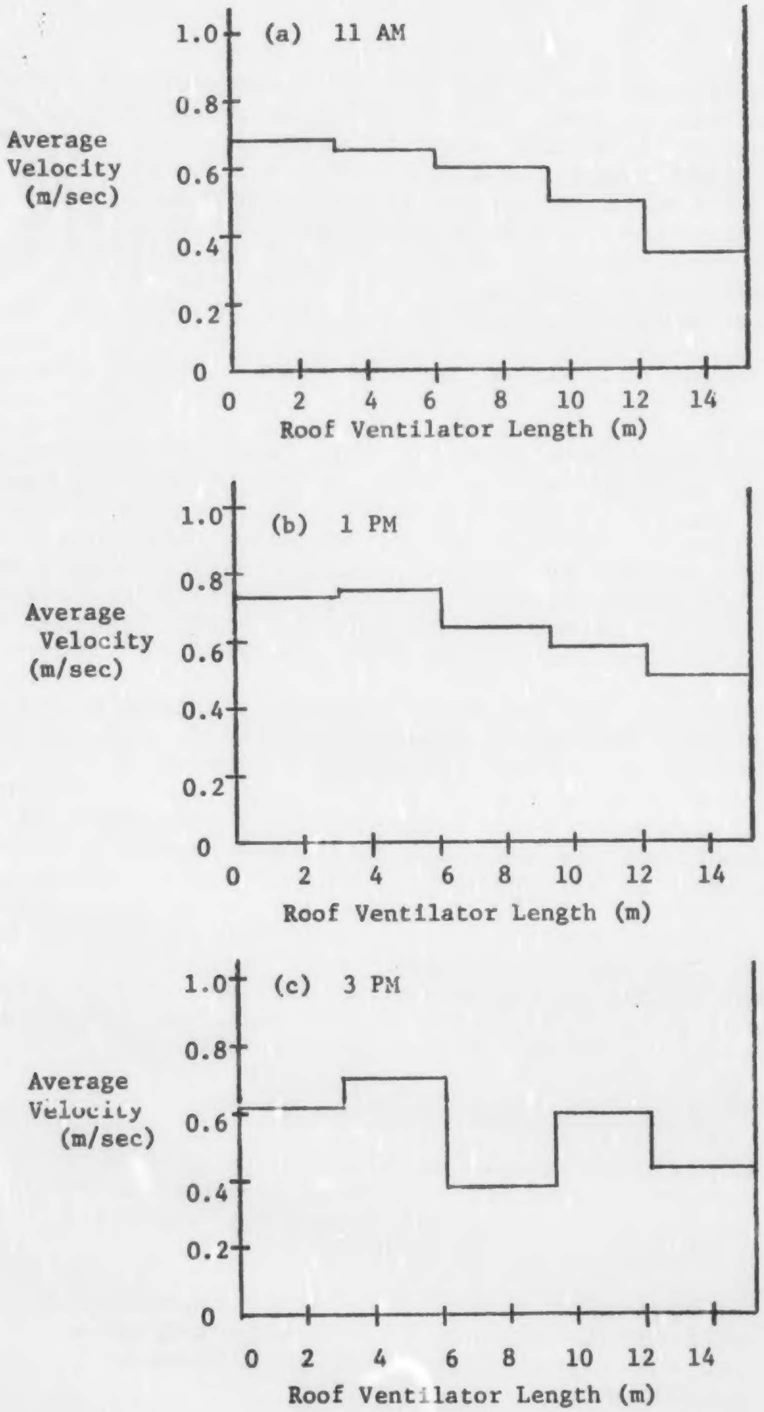


FIGURE 42

AVERAGE VELOCITY PROFILES
FOR ROOF VENTILATOR EMISSION EXAMPLE PROBLEM

The results of these example calculations are shown in Table 11. It can be seen that consideration of the actual variation of concentration and velocity with time and location is not important, since averaging all concentration and velocity data from Figs. 41 and 42 to single values resulted in only a 3.1% difference from the multistep calculation. This result tends to support the applicability of the concept of a manifold system, such as specified in EPA method 14, which results in average concentration measurements from a number of sampling locations.

Considering only averaged data from 3 sample stations, the center and both ends of the monitor, also had little effect on the calculated total emission, resulting in a 5.8% difference. However, when only data from a single port was used to calculate the emission from the entire 15.24 m length of roof ventilator, the "error" ranged as high as 74.4%. This result might cause one to question the wisdom of the velocity measurement specification of EPA Method 14, which requires only a single measurement point for every 85 m of length. The flow through aluminum potroom roof ventilators may be more uniform than that encountered at the Hitchcock Industries field test site, however.

To summarize, the sampling technique demonstrated through the test program described above consists of velocity and particulate concentrations at an unspecified number of sampling stations near the base of the roof ventilator, using widthwise velocity surveys with heated thermopile anemometers to determine average velocities and constant flow rate sampling with high volume samplers to determine particulate concentrations. An as yet unanswered question is the required number of simultaneous sampling locations over the large emission surface of a given roof ventilator. Engineering judgment will be required with regard to the expected degree of variation of effluent stream characteristics with position along the length of the roof ventilator and various economic factors involved in conducting the tests.

F. Applicability to Other Emission Sources

The sampling technique developed for this example of a low velocity, extended dimension emission source can be generalized to other low velocity, extended dimension sources in terms of three basic choices:

1. Selection of suitable velocity instrumentation having sufficient accuracy in the expected velocity range, yet sufficient durability to withstand field test conditions.

2. Selection of a high volume particulate sampler to ensure sufficient volume of gas sampled to obtain useful results.

TABLE 11

CALCULATED EMISSIONS FOR EXAMPLE PROBLEM

Total Emission, $E = \sum_{i=1}^{N} \sum_{j=1}^{M} (C_j \overline{V}_j A_j) t_i$

N	M	C_j (gm/m^3)	$\overline{V}_j$ (m/sec)	A_j (m^2)	t_i (sec)	E (gm)	% Difference
3	5	Individual values From Fig. 41 a,b,c	Individual values From Fig.42a,b,c	5.58	7200	79.8	-
3	1	Average values From Fig.41a,b,c	Average values From Fig.42a,b,c	27.9	7200	82.7	+3.6
1	1	Average value From Fig. 41	Average value From Fig. 42	27.9	21,600	82.3	+3.1
3	3	Individual values From Fig.41a,b,c at Stations 1,3,5	Individual values From Fig.42a,b,c, at Stations 1,3,5	9.3	7200	81.3	+1.9
1	1	Average value From Fig. 41 at Stations 1,3,5	Average value From Fig. 42 at Stations 1,3,5	27.9	21,600	84.4	+5.8
3	1	Individual values From Fig. 41 at Station 3	Individual values From Fig 42 at Station 3	27.9	7200	133.4	+67.2
1	1	Average value From Fig. 41 at Station 3	Average value From Fig. 42 at Station 3	27.9	21,600	139.2	+74.4
1	1	Average value from Fig. 41 at Station 5	Average value from Fig. 42 at Station 5	27.9	21,600	49.2	-38.3

3. Selection of appropriate sampling locations where external disturbances are minimized and sufficient information can be obtained to assess the total emissions.

The general concept should be applicable to any low velocity, extended dimension emission source where satisfactory choices can be made.

In certain cases, the heated thermopile type velocity instrument may be unsuitable, such as in basic oxygen furnace (BOF) shop ventilators, where the effluent streams reportedly are characterized by temperatures above the operating limit of this instrument. Several velocity instruments are discussed in the Appendix, which can be used as a guideline for selection of suitable velocity instrumentation.

The selection of sampling locations presents the principal problem in adapting the method to other sources, since a clear representation of this aspect was not possible within the scope of the present study.. Again, at this point in time, engineering judgment must play a large role in determining the number of sampling points needed.

IV. WET SCRUBBER SAMPLING TECHNIQUES

The principal characteristic of the flow downstream of a scrubber is the presence of saturated gas and/or entrained liquid droplets. It was determined that various problems associated with this characteristic, and with the various devices used to remove liquid droplets from the flow (mist eliminators), generally cause the standard Method 5 sampling train to be inadequate for emission measurements. In order to examine possible alternative sampling techniques, a program of methodology review, field testing and model testing, following the same basic approach taken for the study of roof ventilator sampling techniques, was undertaken.

A. Review of Sampling Methodology

A wide variety of sampling equipment has found application in sampling scrubber exhaust streams, including such devices as wet and dry impingers, impactors with various substrates, cyclone precutters, and fabric filters. This is due in part to the wide variety of pollutants, both gaseous and particulate, which are found in scrubber applications. A partial list of particulate sampling trains used by various organizations may be found in Ref. 35.

Several aspects which must be considered in scrubber emission measurements are specified in Refs. 36 and 37. When sampling a wet scrubber system, particulate concentration should be analyzed on a dry gas basis so that inlet and outlet conditions can be compared for a realistic collection efficiency computation. Thus, the dry gas flow rate and the volume of entrained liquid must be measured. In addition, isokinetic sampling is very important since droplet sizes may have a wide range depending on the particular entrainment separator used.

Scrubber sampling methods have usually specified that the sample probe be heated (Refs. 16,22,35). The required temperatures may be critical depending on both the chemical makeup of the exhaust gas and the sampling train. Temperatures should generally remain above the scrubber fluid dewpoint, but not so high as to vaporize various liquid pollutants of interest. As in the case of roof ventilator sampling, engineering judgment plays a large role in the selection of sampling equipment and techniques (Refs. 17, 36).

A great deal of information concerning sampling techniques and problems was obtained through contacts with twelve manufacturers of wet scrubber systems. Since scrubber manufacturers often tend to specialize in wet scrubber systems for a particular industry, the sampling techniques used vary according to the type of pollutants encountered in these various industries. The most common practice was found to be use of the basic Method 5 sampling train with modifications required to overcome specific problems encountered. Typical modifications include various placements of the filtration assembly relative to the other sampling train components and the use of liquid droplet precutters at the sampling probe inlets. Precutters are usually of the cyclone type, several of which are described in Ref. 37, or inertial impaction separators. One type of precutter is illustrated in Fig. 43. Occasionally, totally different sampling techniques have been employed in particularly troublesome situations.

Other difficulties discussed in these manufacturer contacts included the variation of particulate concentrations in scrubber system ductwork due to gravitational settling and wall impingement and problems associated with sustained high temperature of heated sampling probes. In certain cases, the probe temperature of 121°C (250°F) specified by Method 5 was suspected to cause breakdown of various particulates. Several manufacturers also have encountered unusually large degrees of droplet carryover from the mist eliminators in certain systems, usually in small scrubber systems or systems with high velocities. One manufacturer observed that liquid entrainment became very severe above a critical velocity on the order of 11.7 to 12.7 m/sec (2300 to 2500 ft/min).

Possibly the most common difficulty reported was the presence of cyclonic flow in the stream to be sampled, often induced by the mist eliminator. This problem was observed by many manufacturers. In addition, seven of nine scrubber systems discussed in Ref. 21 had swirling or cyclonic flow. Sampling problems reported in Ref. 21 were handled either by orienting the sample probe in the direction of maximum velocity or by adding permanent "egg crate" or vane-type flow straighteners. The use of flow straighteners ranging from bundles of stove pipes to sophisticated vane arrangements were reported by various manufacturers. Concern was expressed, however, that overall flow rate and particulate concentration may be altered when such flow straightening devices were introduced.

Cyclonic flow presents problems in determination of the volumetric flow rate since the axial component of velocity must be known at all points in a given cross section in order to calculate the volumetric flow rate through that section. A hypothetical cyclonic flow is illustrated in Fig. 44 showing the normal method for finding this axial component, which requires the ability to measure the yaw angle. If an S-type pitot tube were used to attempt direct measurement of the axial component of velocity, the measurement would be in error since the output of a pitot tube does not correspond to the cosine of the yaw angle, as indicated by the data shown in Fig. 45 (extracted from Refs. 2 and 38).

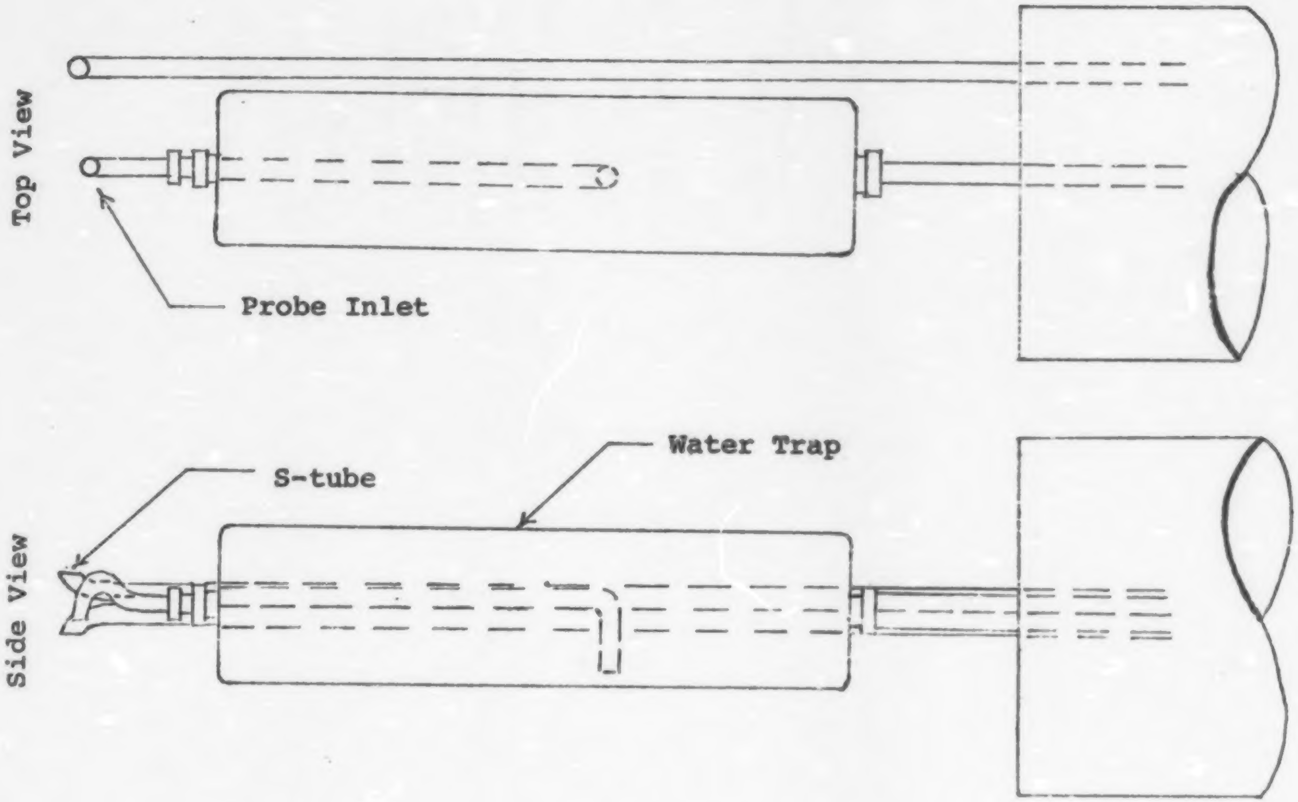

Top View
Probe Inlet
Side View
S-tube
Water Trap

FIGURE 43. INERTIAL IMPACTION LIQUID DROPLET SEPARATOR USED BY A WET SCRUBBER MANUFACTURER'S TEST GROUP

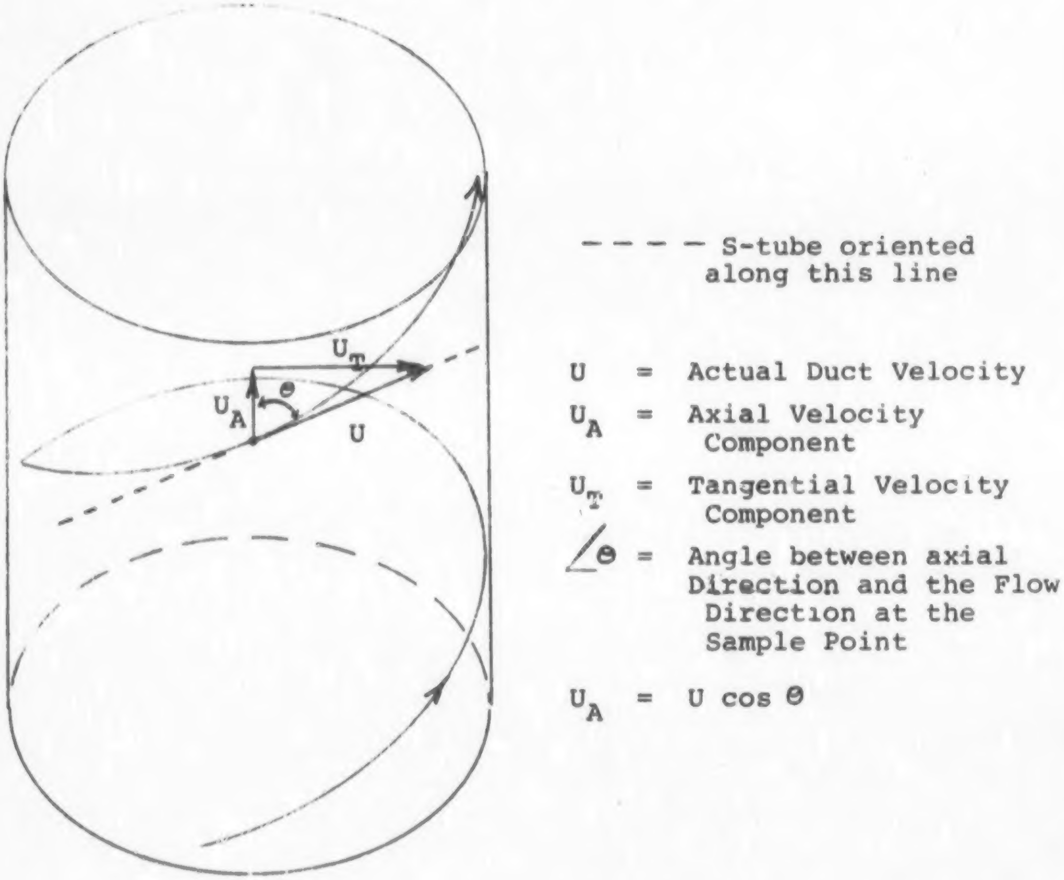

U_T
U_A
θ
U
- - - - S-tube oriented along this line
U = Actual Duct Velocity
U_A = Axial Velocity Component
U_T = Tangential Velocity Component
$\angle\theta$ = Angle between axial Direction and the Flow Direction at the Sample Point
$U_A = U \cos \theta$

FIGURE 44. METHOD USED TO DETERMINE AXIAL COMPONENT IN A SINGLE VORTEX CYCLONIC FLOW

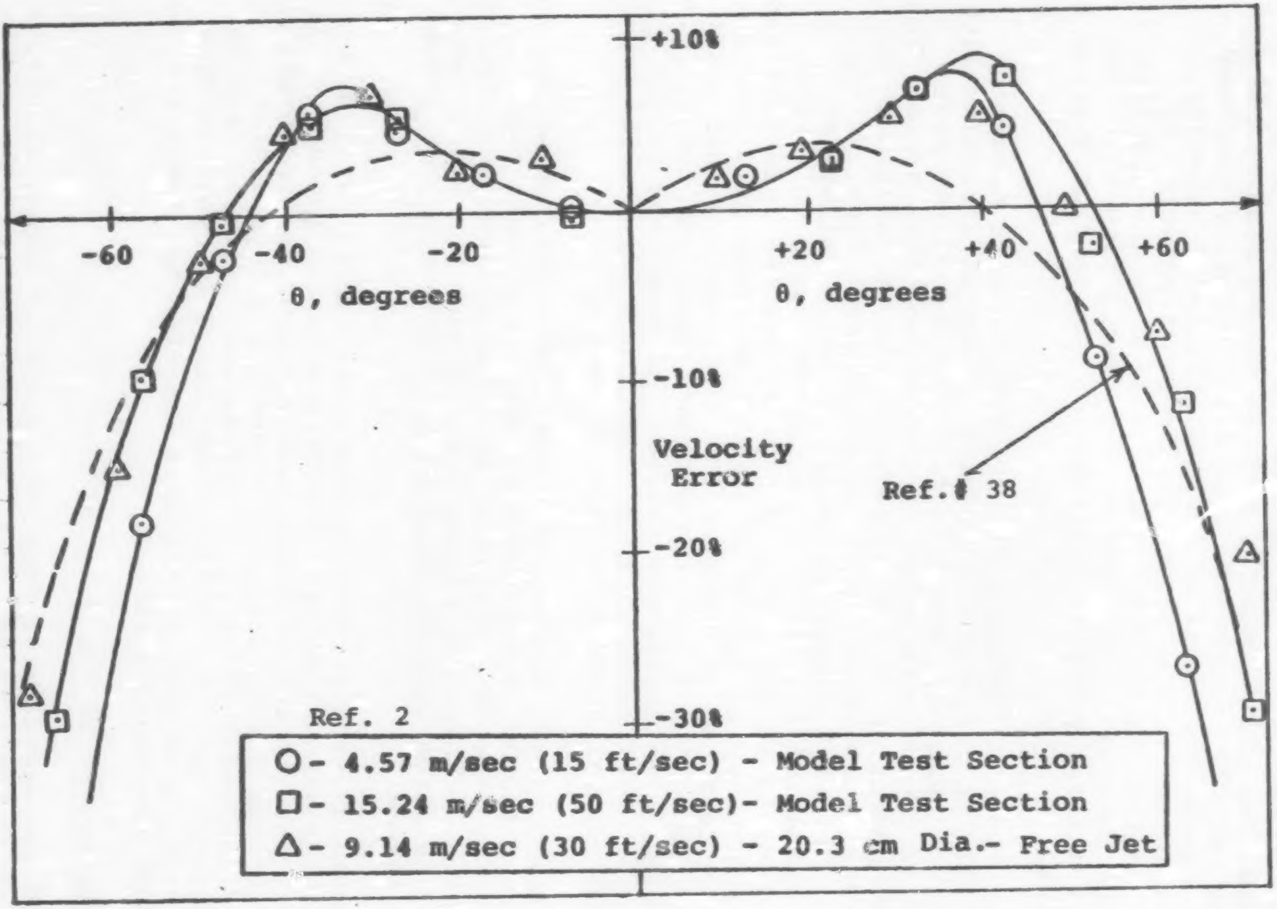


FIGURE 45. VELOCITY ERROR WITH YAW ANGLE (3/8" S-TUBE)

Several studies have been made concerning sampling within vortices or cyclonic flow regions (e.g., Refs. 39-42). It has been observed that in a flow pattern consisting of a vortex motion superimposed on an axial motion, or a single vortex cyclonic flow, the axial velocity profile varies considerably as the swirling velocity increases. The axial velocity component at the duct center decreases relative to the axial velocity component at larger radius values as the swirling velocity increases. Another measurement consideration is the possible effect of the inserted probe size on a cyclonic flow (Ref. 39). Insertion of a large probe in a small duct can readily disturb a cyclonic flow.

Various types of instruments have been used to determine volumetric flow in cyclonic flow fields. Several directionally sensitive pitot tubes are shown in Fig. 46. One of the most widely used is commonly referred to as the Fecheimer probe. The principle of operation of the Fecheimer probe is related to the pressure distribution around a cylinder in cross flow, as shown in Fig. 47. The static pressure angle is quite uniform at 39.25° for values of Reynold's number in the range $10^4 - 2 \times 10^5$. By arranging static pressure taps at the two locations and a total pressure tap as indicated in Fig. 48 (from Ref. 44), the yaw angle can be found by rotating the probe until a null point is reached between the two static pressure taps, and the dynamic pressure is then the difference between the total and static pressure taps. Variations of this concept are illustrated in Figs. 49 and 50, extracted from Refs. 45 and 46.

Other directional sensing velocity instruments appearing in the literature include spherical head direction pitot tubes (similar to Fig. 45), and single or multiple element hot wire or hot thermopile anemometers. These devices have not been used as extensively in large duct cyclonic flow as the Fecheimer probe or its variations.

To summarize, the primary problems related to particulate sampling at the exhaust of wet scrubbers revealed through a survey of literature and contacts with scrubber manufacturers were: 1) various difficulties in recovering the pollutant, either in dissolved form or in an undissolved mixture, from the liquid droplets, and 2) difficulties caused by cyclonic flow often resulting from mist eliminators intended to remove the droplets from the exhaust stream.

B. Preliminary Field Tests

The Seneca Waste Water Treatment Plant in Eagan, Minnesota, was selected as the site for initial field testing. The air pollution control system at this site includes two Peabody impingement tray scrubbers downstream of a twin incinerator system used to burn the sewage sludge obtained from the final

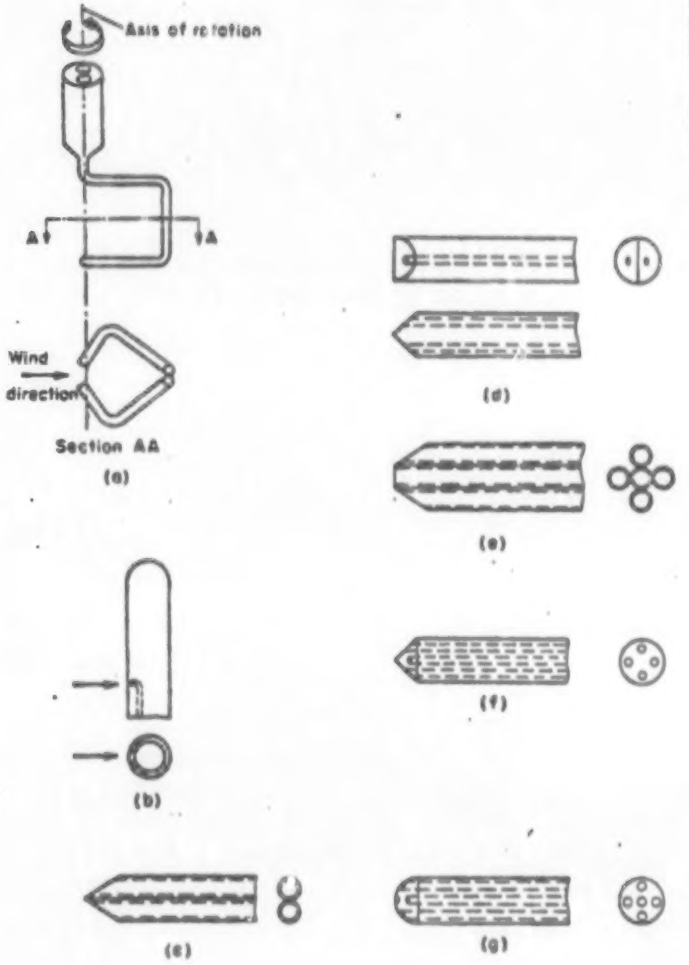

Axis of rotation
A
A
Wind
direction
Section AA
(a)
(b)
(c)
(d)
(e)
(f)
(g)

FIGURE 46. SEVERAL TYPES OF DIRECTIONAL PITOT TUBES
(REF. 43)

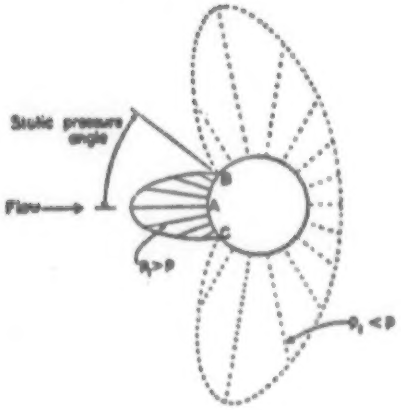

Static pressure angle
Flow
B
A
C
$p_t > p$
$p_t < p$

FIGURE 47. PRESSURE DISTRIBUTION OVER A CYLINDER IN CROSS FLOW

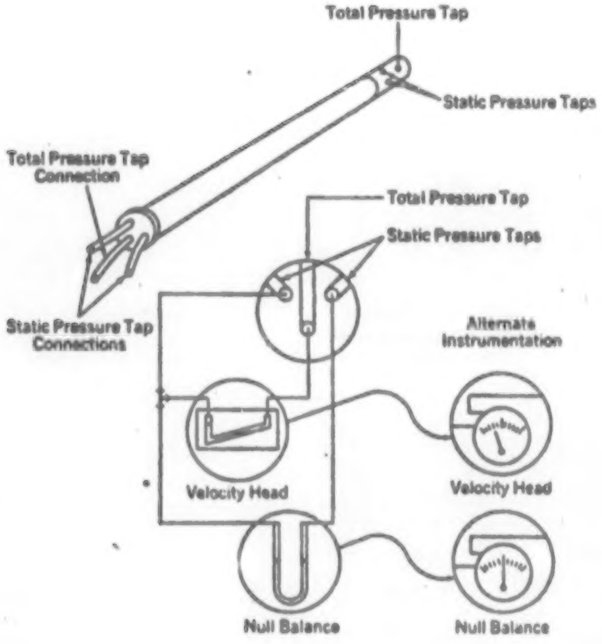

Total Pressure Tap
Static Pressure Taps
Total Pressure Tap Connection
Total Pressure Tap
Static Pressure Taps
Static Pressure Tap Connections
Alternate Instrumentation
Velocity Head
Velocity Head
Null Balance
Null Balance

FIGURE 48. TYPICAL FECHEIMER PROBE AND PRESSURE MONITORING SYSTEM (REF. 44)

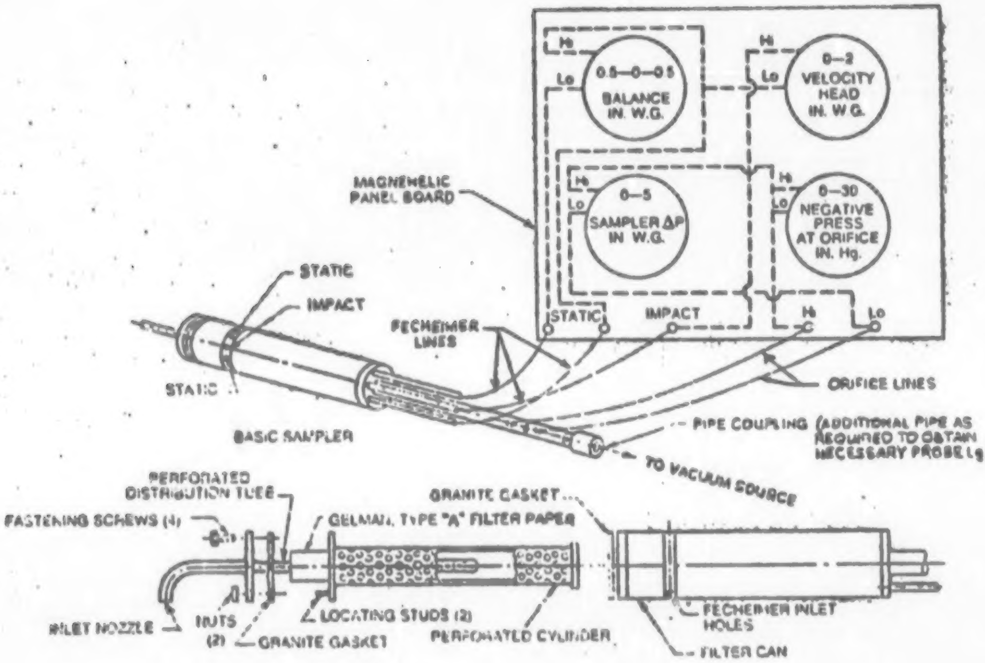

Hi
Lo
0.5—0—0.5
BALANCE
IN. W.G.
Hi
Lo
0—2
VELOCITY
HEAD
IN. W.G.
MAGNEHELIC
PANEL BOARD
Hi
Lo
0—5
SAMPLER ΔP
IN W.G.
Hi
Lo
0—30
NEGATIVE
PRESS
AT ORIFICE
IN. Hg.
STATIC
IMPACT
STATIC
IMPACT
Hi
Lo
FECHEIMER
LINES
ORIFICE LINES
STATIC
BASIC SAMPLER
PIPE COUPLING (ADDITIONAL PIPE AS REQUIRED TO OBTAIN NECESSARY PROBE Lg)
TO VACUUM SOURCE
PERFORATED
DISTRIBUTION TUBE
FASTENING SCREWS (4)
GELMAN TYPE "A" FILTER PAPER
GRANITE GASKET
INLET NOZZLE
NUTS
(2)
GRANITE GASKET
LOCATING STUDS (2)
PERFORATED CYLINDER
FECHEIMER INLET
HOLES
FILTER CAN

FIGURE 49. FECHEIMER PROBE BUILT INTO FILTER HOLDER (REF. 45)

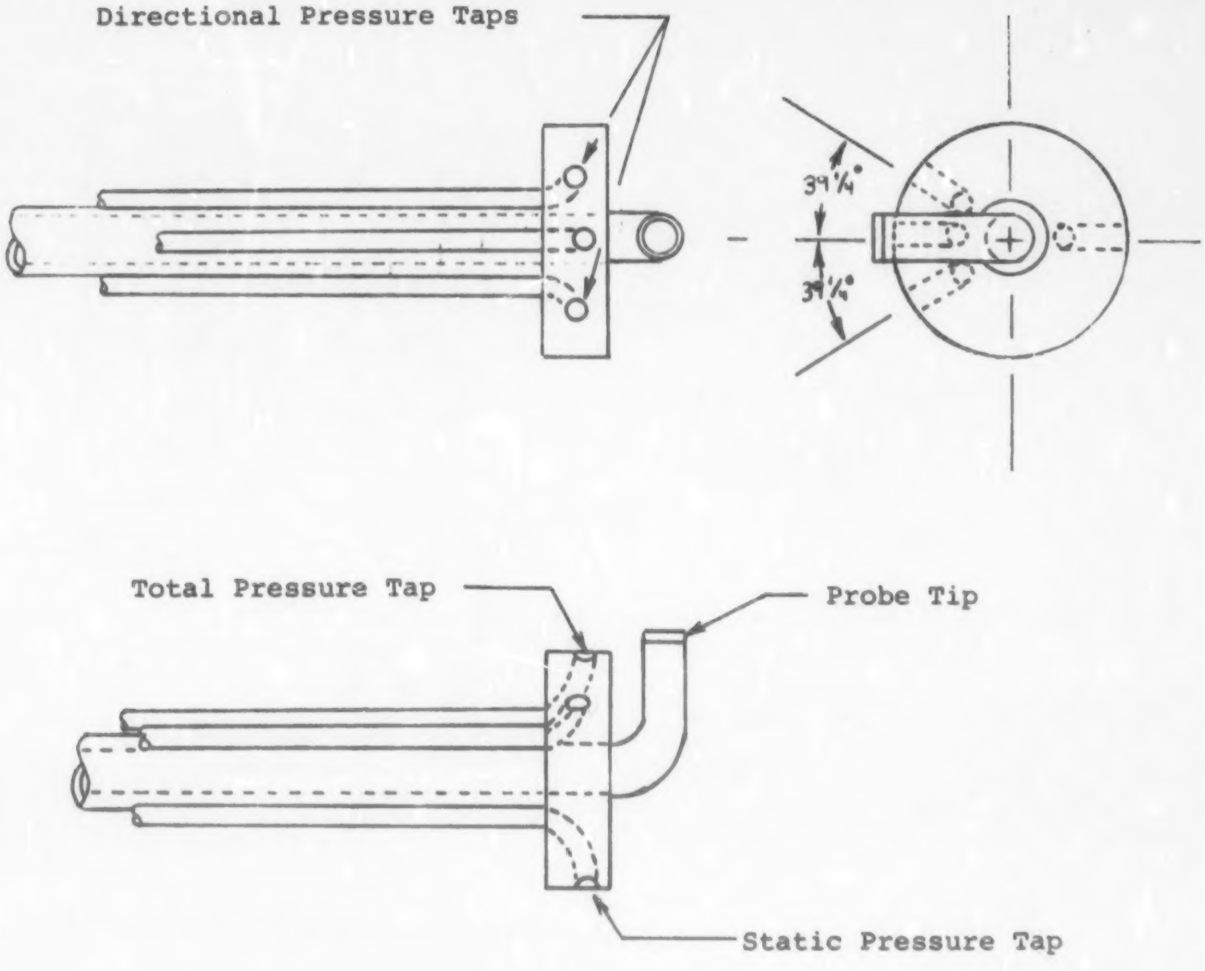

Directional Pressure Taps
39¼°
39¼°
Total Pressure Tap
Probe Tip
Static Pressure Tap

FIGURE 50. CONNECTICUT STATE DEPARTMENT OF ENVIRONMENTAL PROTECTION PROBE (REF. 46)

process at the treatment plant. The flow rate capacity of these scrubbers is 340 m^3/min (12,000 ft^3/min). Impingement tray scrubbers of this size are commonly found within the industrial community, particularly in the collection of particulate matter from incinerators. A diagram of the wet scrubber system and the exhaust ducting is shown in Fig. 51. Each scrubber has a fixed vane type centrifugal mist eliminator at the exhaust end.

The sampling train assembled for preliminary field testing followed EPA Method 5 specifications, including a glass lined heated probe and attached S-tube, a filter holder, two wet and two dry impingers or a condenser apparatus, a container of silica gel desiccant, a vacuum pump, a dry gas meter and a rotameter. A Fecheimer probe was selected to measure flow angularity. After the angle of flow was determined at a given location, the sample probe and S-tube were oriented in the flow direction as determined by the Fecheimer probe. Velocity was then measured with the S-tube, and isokinetic sampling was achieved by adjusting the flow to the S-tube measured velocity.

The first sampling in the series of preliminary field tests was accomplished at points upstream and downstream of the I.D. fan, at the sample ports shown in Fig. 51. A number of observations were made concerning the exhaust stream characteristics at these two locations.

A large degree of cyclonic flow was present at the upstream sampling location, with yaw angles as large as 60° being measured. The measured velocities ranged from 12.2 m/sec to 17.0 m/sec. The duct walls were moist at this location, but only a small amount of liquid droplets were detected in the sampling train. The flow downstream of the I.D. fan, however, was much more uniform, and liquid droplets were present to such a degree as to thoroughly wet the sampling probe. Large pressure drops occurred quickly as droplets built up on the filter mats and the vacuum pump was not able to maintain isokinetic sampling rate, forcing sampling times to be kept very short. The average particulate concentration measured at the two locations also differed, being 97 mg/Nm^3 upstream and 61 mg/Nm^3 downstream of the fan.

An illustration of these differences was provided by placing the filter holder immediately after the sample probe nozzle. Filter samples taken upstream and downstream of the fan using this arrangement are shown in Fig. 52. It can be seen that the upstream filter is much more uniform in density of collected particulate than the downstream filter. Whether or not the presence of liquid droplets was the cause for the rather uneven collection of particulate at the downstream location was not determined.

Another aspect of the first field tests was an investigation of the degree of particulate lost on the walls of the glass

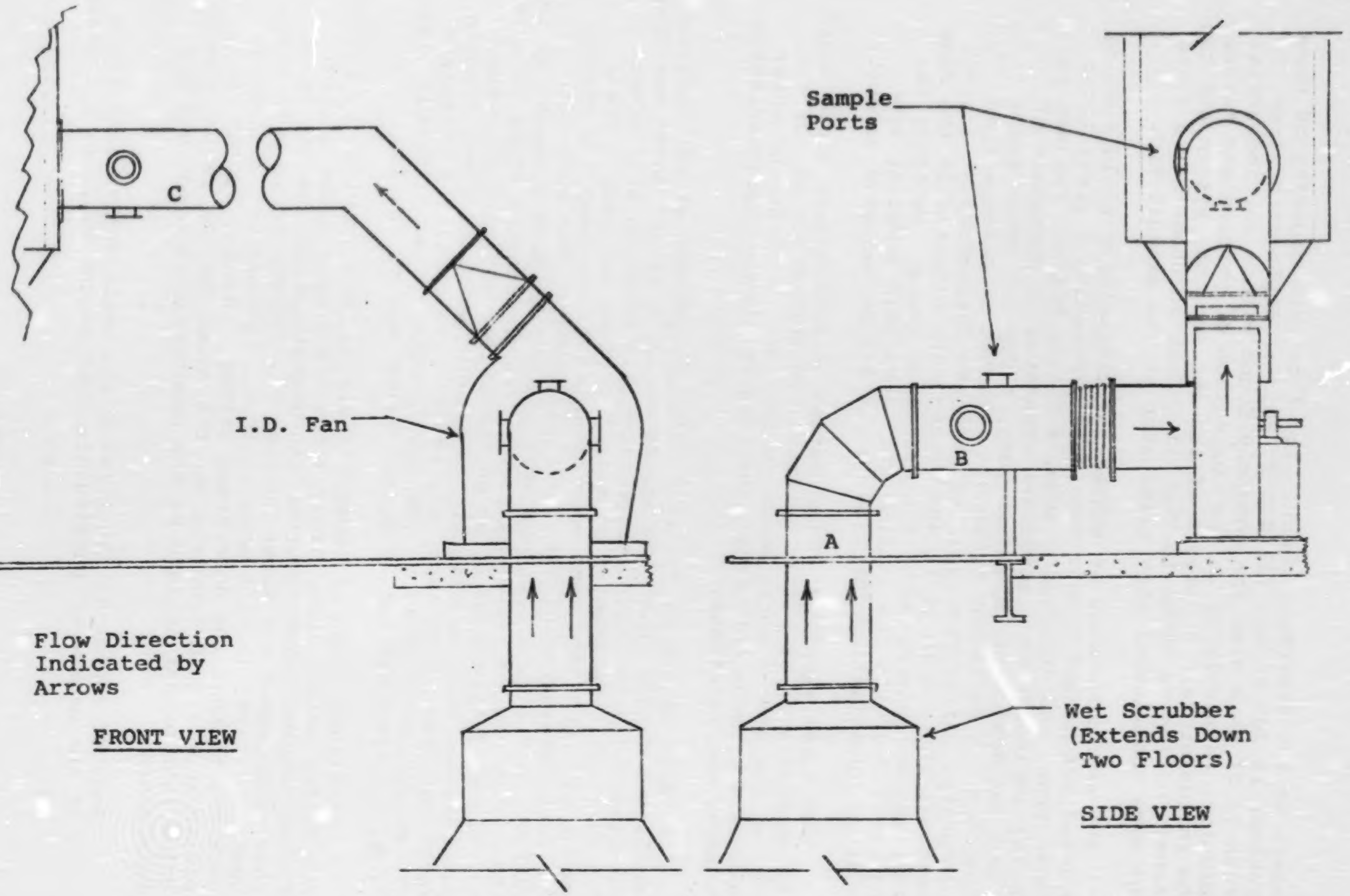

Sample Ports
C
I.D. Fan
B
A
Flow Direction Indicated by Arrows
FRONT VIEW
Wet Scrubber (Extends Down Two Floors)
SIDE VIEW

FIGURE 51. WET SCRUBBER AND EXHAUST DUCTS AT THE SENECA WASTEWATER TREATMENT PLANT EAGAN, MINNESOTA

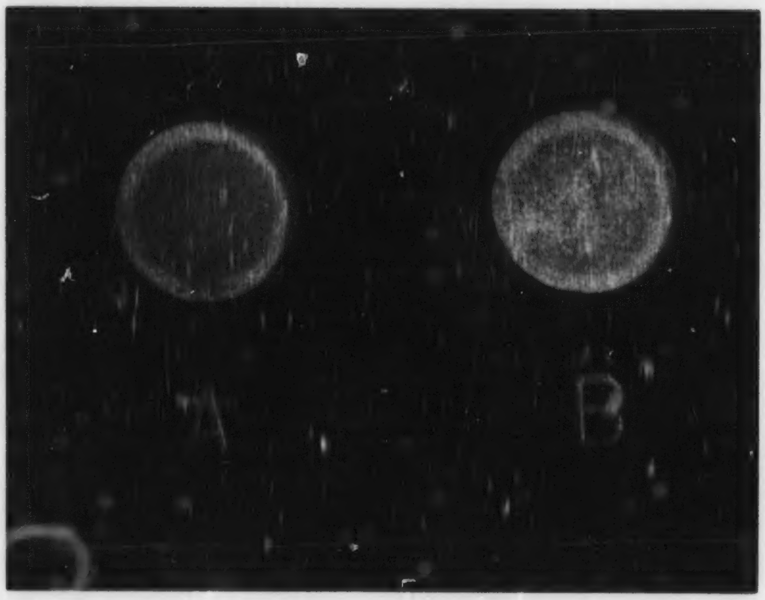


FIGURE 52. FILTER SAMPLES TAKEN AT SENECA WASTEWATER TREATMENT PLANT DURING PRELIMINARY FIELD TESTS

A = UPSTREAM OF I.D. FAN

B = DOWNSTREAM OF I.D. FAN

lined probe due to impingement and gravimetric settling of liquid droplets. The probe was sealed after a series of tests and returned to the FluiDyne Laboratories, where it was cleaned and all particulate matter deposited within the probe was collected. It was found that the losses within the probe amounted to 13% of the total collected particulate.

Following the first series of field tests, sampling ports were installed at point A in Fig. 51, just downstream of the scrubber. Installation costs were shared by the Metropolitan Waste Commission, whose members were very helpful and cooperative during the field test study. In addition to the added sample ports, a modification of the sample train was made in order to alleviate the problems observed in the liquid droplet environment. This consisted of adding an inertial precutter to the sampling train, followed directly by the filter holder, as illustrated in Figs. 53 and 54. The precutter was designed and built by FluiDyne from stainless steel. The design particle cut size is 10 μ; larger particles are impacted on the cylinder wall and collected within the container, to be removed after each sampling run for analysis.

After these modifications to the ductwork and the sampling train had been completed, a second series of preliminary field tests was made. The tests included 48-point velocity surveys and 12-point particulate concentraton surveys at the new sample location (point A in Fig. 50) and downstream of the I.D. fan. Again, the Fecheimer probe was first used to determine the yaw angle of the flow at each sample point. A flow direction tuft was then used to visually determine the yaw angle as a check, since the Fecheimer probe was rather large (2.54 cm or 1 in) for the ducting being sampled. The visually determined angle in all cases confirmed the indications of the Fecheimer probe. The sample probe and S-tube were then oriented in the measured flow direction, the velocity was measured, and an isokinetic exhaust gas sample was extracted.

Typical total velocity and axial velocity component profiles are shown in Fig. 55. When the axial velocity component was used to calculate volumetric flow rates at the scrubber exhaust (point A) and downstream of the I.D. fan, the results agreed to within 6%, indicating that this method of velocity determination is useful in cyclonic flow of the type observed in this field test situation. The degree of cyclonic flow at the scrubber exhaust was severe, with yaw angles as large as 75°, while the flow downstream of the fan had a very small degree of cyclonic motion.

Average particulate concentration was again seen to vary from 100 mg/Nm^3 at the scrubber exhaust to 41 mg/Nm^3 downstream of the fan on one day of testing, in relatively close agreement

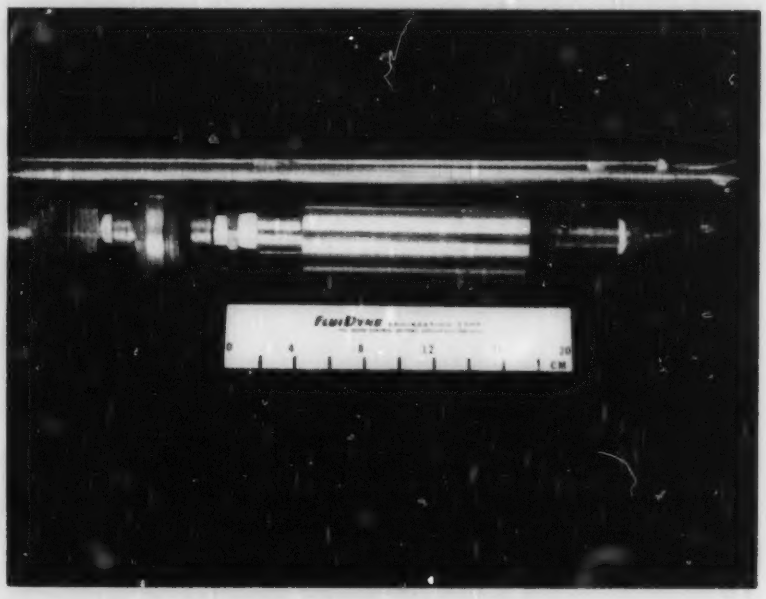

FluiDyne
0
4
8
12
20
CM

FIGURE 53. INERTIAL SEPARATION PRECUTTER USED IN PRELIMINARY FIELD TESTS AT SENECA WASTEWATER TREATMENT PLANT

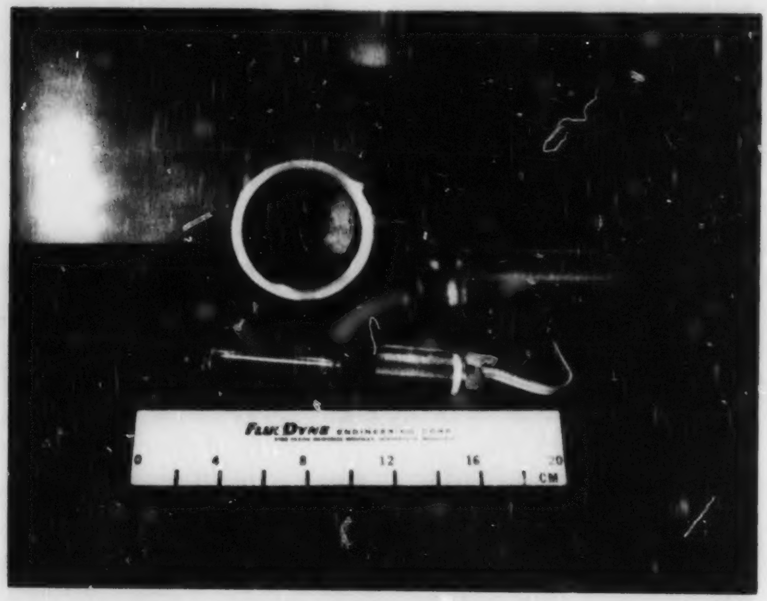

FluiDyne
0
4
8
12
16
20
CM

FIGURE 54. INTERNAL VIEW OF INERTIAL SEPARATION PRECUTTER

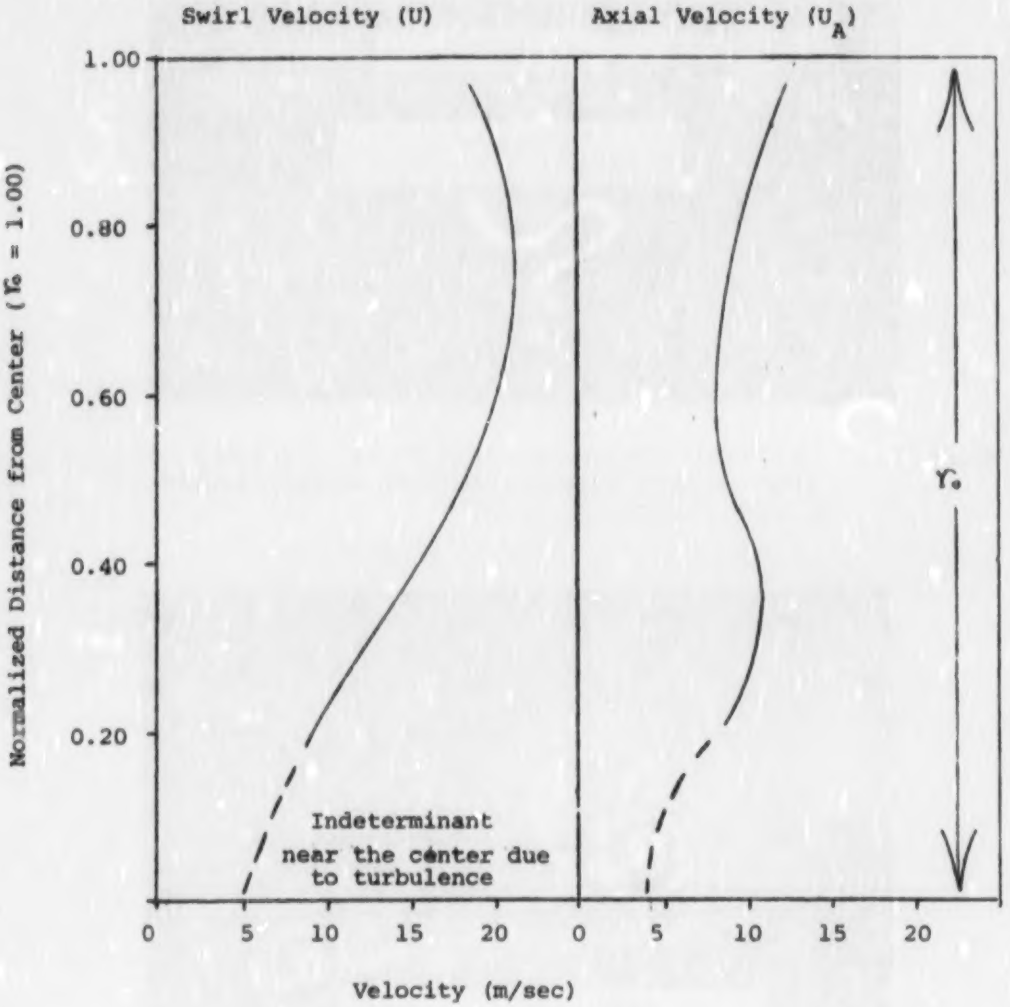


FIGURE 55. TYPICAL VELOCITY PROFILE OBTAINED DURING PRELIMINARY FIELD TESTS AT SENECA WASTEWATER TREATMENT PLANT

to the first measurements. Measurements made on the following day indicated a concentration of 56 mg/Nm^3 at the scrubber exhaust, however.

The inertial precutter appeared to eliminate the problem of rapid increase in pressure drop due to buildup of droplets on the filters. When the precutter was opened after sampling, however, no liquid was found. When the water vapor content was measured with an Alnor dewpoint indicator, the exhaust stream was found to have only a 79% relative humidity. Thus, it was concluded that the liquid droplets impacted on the wall of the precutter were evaporated due to the non-saturated conditions. This interesting finding leads to the conclusion that one should not assume a saturated stream based on the presence of liquid droplets as suggested in Method 5 and that an accurate hygrometer or wet/dry bulb thermometer readings should be used to calculate water vapor content. Large discrepancies in total water vapor content calculated from dewpoint measurement and by the Method 5 calculation were also observed in Ref. 47.

The variation in liquid droplet concentration is probably explained by the cyclonic flow resulting from the mist eliminator. Droplets which pass through the mist eliminator are driven to the duct walls by the cyclonic flow and pass along the walls into the I.D. fan, where they are evenly distributed and re-entrained by the flow leaving the fan.

In summary, the preliminary field tests of a scrubber exhaust stream provided a number of observations. The described method for evaluation of the cyclonic flow field appears to have merit. Some method for reducing the amount of liquid droplet buildup on the filters is necessary. The inertial precutter did appear to accomplish this goal, although the subsequent evaporation of the liquid made recovery of the particulate carried by the impacted droplets after each sample difficult. Determination of liquid content by means of an accurate instrument is necessary.

C. Model Studies

Following the overall testing plan outlined for the completion of this study program, a laboratory model was designed to simulate typical flow situations occurring in the exhaust streams of wet scrubbers. The overall design concept is illustrated in Fig. 56. The model is to use the same blower as used to power the roof ventilator model. A fixed vane type cyclonic mist eliminator was purchased from Peabody Engineering Corp., Stamford, Connecticut, to be placed in the model in order to simulate actual flow profiles. Liquid droplets and particulate matter will be introduced into the model by means of a spray nozzle. At the present writing of this report, the model is under construction at the FluiDyne Medicine Lake Aerodynamic Test Facility.

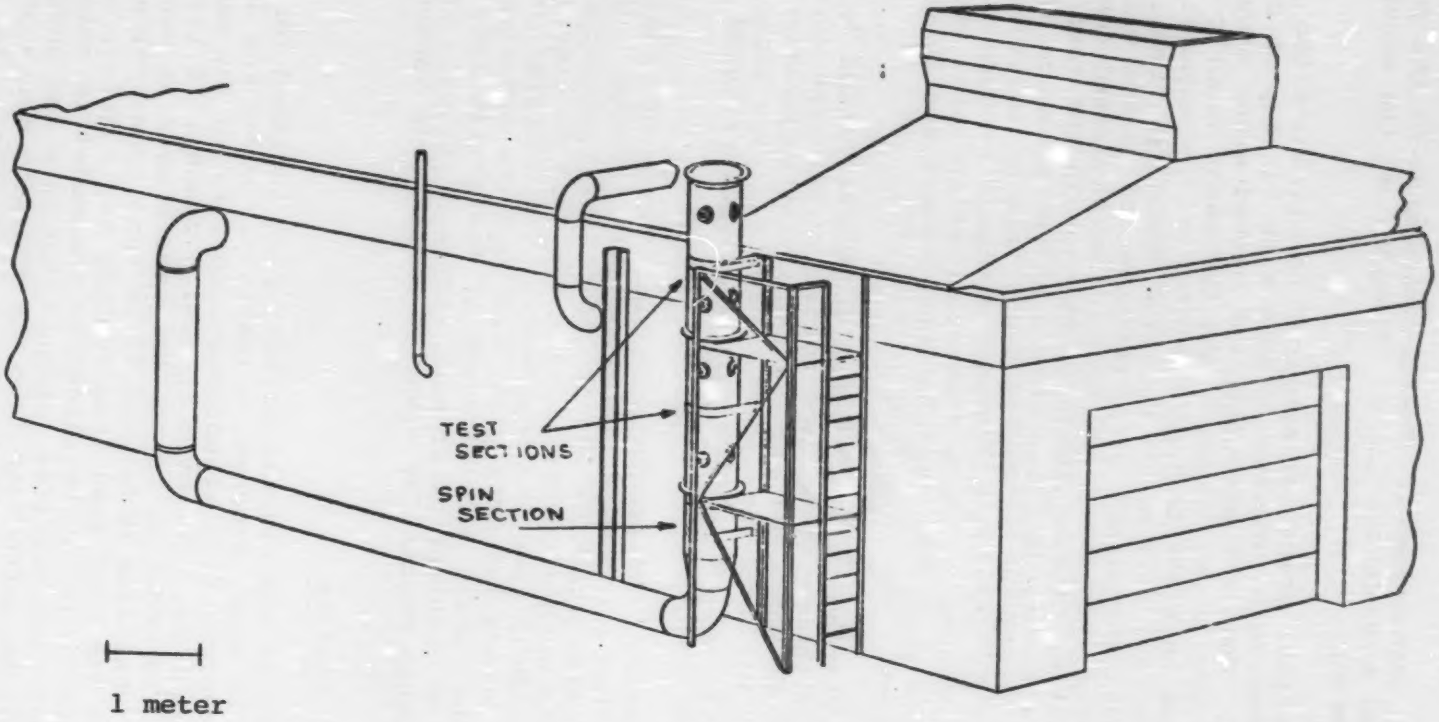

TEST SECTIONS
SPIN SECTION
1 meter

FIGURE 56. PROPOSED CYCLONIC FLOW AND ENTRAINED LIQUID DROPLET TEST SYSTEM LOCATED AT THE MEDICINE LAKE AERODYNAMIC TEST FACILITY

AS VIEWED FROM THE SOUTHWEST

V. FUTURE WORK

A. Wet Scrubber Sampling Techniques

Future efforts will be directed toward evaluation of sampling techniques in the flow model described in Section IV-C. Initial studies will concentrate on the selection of appropriate velocity instrumentation for proper computation of volumetric flow rate in the cyclonic flow field produced by the mist eliminator. The second phase of model testing will attempt to evaluate the accuracy of selected sampling trains in measuring the concentration of particulate introduced in the flow. The particular sampling train configuration determined to best fit the requirements of the scrubber application will then be evaluated in a final field test, and conclusions and recommendations will be made as to its usefulness in emission measurement in other emission sources with saturated gas streams or entrained liquid droplets.

B. Grain Dryer Sampling Techniques

A program following the same plan as used in evaluating roof ventilators and wet scrubbers will be undertaken for the study of grain dryer emission measurement. A review of presently used sampling methodology will be followed by a preliminary field test in order to determine typical sampling problems and conditions. A laboratory model will then be constructed using the existing blower and ductwork at the Medicine Lake Aerodynamic Test Facility, and a model test program will be performed to evaluate techniques and instrumentation for measurement of grain dryer emissions. The final sampling technique will be further tested in the field, if necessary, and evaluated as to its usefulness with other partially confined emission sources.

VI. INTERIM CONCLUSIONS AND RECOMMENDATIONS

The test program for evaluating roof ventilator emissions led to the conclusion that a combination of a high volume particulate sampler and a heated thermopile anemometer provide a reasonable, conservative estimate of total particulate emission through a cross section of a roof ventilator when deployed at a sampling location near the base of the ventilator. Widthwise velocity surveys of on the order of 4 to 6 points at each sampling location were required to determine the average velocity. The number of sampling locations required to obtain a given emission measurement accuracy for a given length of roof ventilator must be determined for each specific application; an example based on field tests at a secondary aluminum foundry showed that three sampling locations were needed for a 15.24 m ventilator. Engineering judgment should be used to determine a balance between economic considerations and the maximum amount of information obtainable in selecting a number of sampling locations when making emission measurements at a given location.

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APPENDIX

VELOCITY INSTRUMENTATION FOR LOW VELOCITY, PARTIALLY CONFINED SOURCE PARTICULATE SAMPLING

By

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A1.0 INTRODUCTION

Procedures and instrumentation for the determination of velocity and particulate concentration have been established and studied for emission sources having well-defined flow fields and velocities above 1.5 to 2 m/sec (Ref. A1). Little information is available, however, concerning procedures and instrumentation applicable to emission sources for which the flow is not well defined or the effluent stream is not confined. An example of such an emission source is the roof monitor or roof ridge ventilator. This type of emission source is characterized by low velocities and complex, often circulatory, flow fields.

Knowledge of the velocity of an emission stream is necessary for determination of the volumetric flow rate, which must be known in order to establish the total particulate emission level. A further requirement for establishing the velocity is dictated by the need to establish isokinetic sampling rates, although this is typically not of great importance in the study of roof ventilators due to the small size of particulate generally emitted by such sources.

Measurement of the velocity and determination of the volumetric flow rate are complicated by low velocities and circulatory flow, as opposed to the situation existing in power plant ducting and exhaust stacks, for example. In such a situation, it has been shown (Ref. A2) that a small number of measurements with an S-tube over the cross section of a duct or stack can often provide an accurate determination of the volumetric flow rate. At low velocities (approximately 1 m/sec or less), however, the S-tube or pitot static tube introduce a high degree of uncertainty to velocity measurements due to the extremely small magnitude of the dynamic pressure of the gas stream. In addition, the possibility of regions of reverse flow and large degrees of nonuniform flow angularity in unconfined source emissions requires the determination of the flow direction as well as velocity magnitude in order to establish the net volumetric flow rate.

Thus, the selection of suitable velocity instrumentation for use in connection with low velocity, unconfined sources is an important consideration. Therefore, the suitability of a number of velocity instruments was evaluated for this purpose.

A2.0 TYPES OF VELOCITY INSTRUMENTS

Several types of velocity measuring instruments are listed in Table A1 along with some brief comments concerning the characteristics of each type. There are generally several manufacturers for each type of instrument, but those listed in Table AI proved a representative sample. A brief description of the principle of operation and an evaluation of the possible usefulness of each type of instrument is included in the following.

A2.1 Pitot static Tubes or S-Tubes

The principle of the pitot static tube or S-tube is to measure, be means of a probe inserted in the flow, the difference between total pressure and static pressure (or nearly static pressure, in the case of the S-tube). Thus, the dynamic pressure (or a quantity proportional to the dynamic pressure) is obtained directly from the measurement, and the velocity may be computed if the fluid density is known. This type of instrument is widely used for velocity measurement, and the S-tube is the standard EPA-approved instrument for sampling in ducts and stacks. However, since the dynamic pressure is extremely small in low velocity gas flows, accuracy of measurements becomes poor. In addition, determination of flow direction is not a suitable application for a standard pitot static tube or an S-tube.

The useful velocity range of the S-tube can be extended to some extent with the use of a purge gas flow through the S-tube and a fluidic amplifier. The principle of such an instrument involves a pneumatic bridge between the two S-tube lines, which is balanced in the no-flow condition. As a pressure differential develops between the two S-tube ports, a secondary flow of purge gas is induced in the pneumatic bridge which is proportional to the fluid velocity. This arrangement not only extends the low velocity range of the S-tube to approximately 15 m/min, but also prevents fouling of the tube in a particulate stream, since no fluid actually enters the S-tube. However, the accuracy of this instrument is poor in the very low velocity range.

A2.2 Vane or Propeller Anemometers

A vane or propeller anemometer is positioned normal to the flow velocity. The flow through the anemometer imparts aerodynamic force to the vanes, or propellor, which then rotate at a rate proportional to the fluid velocity. In a mechanical anemometer, the rotation of the instrument is recorded on a dial as a cumulative linear distance, which provides the fluid

TABLE A-1

LOW VELOCITY INSTRUMENTATION

INSTRUMENT	VELOCITY RANGE (ft/min)	MAX.OPER. TEMP. (°F)	FUNCTIONING IN PARTICULATE STREAM	ACCURACY AT 1 ft/sec	DIRECTIONAL SENSITIVITY	RUGGED-NESS	TYPICAL INSTRUMENT MANUFACTURER	TYPICAL INSTRUMENT MODEL	APPROX. COST	COMMENTS
Pitot Tubes or S-Tubes										
1.with Inclined Manometer	600+	800+	Only limited by probe blockage	N/A	Yes (S-tube)	Good	Dwyer		$100	
2.with Micromanometer	400+	800+		N/A		Good	Dwyer		$200	Affected by Vibration
3.S-tube with purge flow	50-1500	800+	Good	±50%	Poor	Good	Hastings-Raydist	GSM-ID5K	$1900	Good for uniform flow;auxiliary readout needed below ~ 100 ft/min
Vane or Propeller Anemometers										
4.Vane Anemometer	50-5000	250	Fair	±20%(est)	No	Fair-Good	Flowrite	MRF	$100	Direct Velocity indication
5.Rotating Vane(mech)	30-5000	250	Fair	±20%(est)	± in direction of alignment	Fair-Good	Davis		$200	Cumulative reading
6.Rotating Vane (elect)	25-5000	250	Fair	±20%(est)		Fair-Good	Davis, Gill		$800	Continuous reading
7.Propeller Vane	25-5000	220	Fair	±20%(est)	Yes	Fair-Good	Gill		$500	
8.Propeller with purge gas cleaning	25-5000	220	Good	±20%(est)			Gill		$200 +purge gas system	
Heated Element Anemometers										
9.Hot Wire	10-6000	800	Needs occasional Cleaning	±20%	No	Poor	Thermo-Systems	1610	$1000	Temp. range may vary
10.Hot Film	10-6000	200	Needs occasional Cleaning	±20%	to 0° or 180°	Fair	Thermo-Systems	1650	$500	Response time may be too fast
11.Wedge hot film		500	Needs occasional Cleaning		No	Good	Thermo-Systems	1234H	$1300 w/readout	Not temp. comp.(+ $100 for temp. comp model.)
12.Hot thermopile	10-3000	200	Needs occasional Cleaning	±6%	to 0° or 180°	Good	Hastings-Raydist	PCI-30	$700	Good field instrument.
Fluidic Anemometers										
13.Parallel Jet	30-8000		Tested to 25 g/m^3		Possible	Good	Bowles		$200	
14.Perpendicular Jet	12-3000	400	4.5 g/m^3		Possible	Good	FluiDynamic		$1000	Temp.range may vary
15.Heated tube-purge flow cooled	60-6000		Good	±50%	Possible	Good	Hastings-Raydist	API-6K	$1500	

velocity when divided by the measurement time, or as a direct velocity indication. Electronic instruments provide a continuous signal which can be recorded. The signal polarity can be proportional to the flow direction. A direct velocity indicating vane anemometer does not respond correctly to a reversed flow. A rotating vane anemometer with a cumulative distance indication allows the determination of a net velocity over the measurement time since a reversed flow will cause distance to be subtracted from the cumulative total. When the indicated cumulative distance is then divided by the measurement time, the resulting velocity is the net velocity which has passed through the anemometer. A propeller vane anemometer aligns itself with the flow, thus providing an indication of flow direction as well as velocity.

These instruments allow measurement of lower velocities than do pitot static or S-tubes. However, the rate of rotation is influenced by bearing friction; thus, this type of instrument must be calibrated frequently with wear, and the calibration may be affected by particulate matter. The use of a purge gas flow to clean the bearings is a common means to prevent fouling of the instrument in a particulate stream. In addition, calibrations are nonlinear near zero velocity, causing poor accuracy at velocities near the stated minimum (approximately 7.5-15 m/min) for this type of instrument.

A2.3 Heated Element Anemometers

The principle of operation of hot wire and hot film anemometers is essentially the same. The sensing element (usually platinum wire or film) is heated, either with a constant electric current or to a constant temperature. When the element is introduced in a fluid stream, the heat transfer from the element is proportional to the fluid velocity. The output from these instruments is then either the resistance of the element, with constant current, or the electric current necessary to maintain the heated element at constant temperature, which is proportional to the fluid velocity. Comercially available instruments generally incorporate temperature compensation, so that calibrations are not affected by fluid temperature. Since the heat transfer from the sensing element will change with a significant buildup of particulate matter, this type of instrument will need occasional cleaning for use in a particulate-laden stream, although the hot film type is less susceptible to fouling. Frequent calibration is also advisable.

A heated thermocouple (or thermopile) anemometer also provides output due to the heat transfer from heated elements in a flowing stream. In this type of instrument, the sensing elements are hot junctions of a thermopile, while alternate junctions are not heated to provide for temperature compensation.

The reduced thermocouple current when the hot junctions are cooled by a flowing gas stream is proportional to the velocity. As in the case of hot wire or hot film anemometers, occasional cleaning is necessary in a particulate stream.

Directional sensitivity is not a basic feature of heated element anemometers. However, protective caps designed for some instruments of this type provide the additional capability to determine yaw angle in a flow.

A2.4 Fluidic Anemometers

One type of fluidic velocity measurement instrument incorporates a jet of fluid, compatible with the fluid whose velocity is being measured, which is introduced into the flow, either parallel or perpendicular to the stream. This fluid jet impinges on two sensing ports situated such that the pressure at these two ports is equal for no flow. When introduced into a flowing stream the jet is deflected, causing a pressure differential between the two sensing ports. This differential pressure is the output of the sensor and can be made linear with the velocity depending on the supply pressure for the jet. The parallel jet type sensor requires lower supply pressures than the perpendicular jet type (Ref. A3). The operational principle does not preclude use in moderate particulate concentrations as long as the tubing systems do not become blocked. Two or three sensors could be arranged to determine orthogonal velocity components. If positive and negative pressures can be distinguished, reverse flow should also be detectable with fluidic sensors.

Another type of velocity measurement instrument which employs fluidic principles involves a tube through which purge gas is continually injected into the flow. A pressure differential caused by the flow at two purge gas outlets induces a secondary flow of purge gas through a heated tube inside the instrument. This secondary flow cools the heated tubing and an electrical output results following the same principle as a heated element anemometer. Since the cooling flow is clean purge gas and not the actual flow being measured, this type of instrument would function well regardless of particulate concentration. However, the output is very nonlinear and the minimum velocity is about 0.3 m/sec.

A2.5 Vortex Shedding Anemometer

A new velocity measurement instrument under development employs vortices generated by a strut and counted by an ultra-sonic sensor (Ref. A4). The frequency of vortex generation is directly proportional to the velocity if the Strouhal number of the obstruction is known, thus providing a calibration. The instrument reportedly has great accuracy at velocities as low as 0.5 m/sec, and based on the assumption of a constant Strouhal number over a wide Reynold's number range, should be insensitive to variations in fluid density, temperature and pressure. However, the characteristics of the instrument have not been sufficiently established to make a judgment as to its applicability in particulate streams. A concept for development of a direction-sensitive instrument employing this concept has also been reported (Ref. A4).

A2.6 Ion Deflection Anemometer

This type of instrument utilizes an ion-emitting source in a tube aligned parallel to the flow. The ions are projected radially from the source toward the walls of the tube. A flow through the tube then causes a deflection of the ion stream which is directly proportional to the total mass flow through the tube, from which the velocity is deduced. Flow direction through the tube is also indicated by this type of instrument making it useful in reversed flow situations. The presence of particulate matter in a flow, however, may cause the velocity calibration to be in error. Since the instrument actually senses the flow of mass, a constant velocity flow should give different velocity indications for different particulate concentrations. In addition, the tube would require occasional cleaning, since buildup of particulate could interfere with the ion stream and collector.

A2.7 Sonic Pulse and Laser Doppler Instruments

The sonic pulse type instrument employs the difference in time for oppositely-directed sound waves to travel a fixed distance to deduce the flow velocity. Two-or three-axis systems allow the measurement of velocity components, giving the information needed for volumetric flow evaluation even in highly turbulent flows. Particulate matter should have little effect on such an instrument. The laser Doppler type instrument determines the shift in frequency caused by scattering of a light from a monochromatic source (laser). The scattering is accomplished by particles introduced in the flow, assumed to move with the velocity of the fluid; thus, the velocity associated with the measured Doppler shift is the velocity of the fluid. In a flow containing various sized particulates, some of which do not move with the fluid velocity, the instrument could be affected by random light scattering by the particulate matter. The major obstacle in consideration of both of these types of instruments, however, is the prohibitively high cost. In addition, the laser Doppler method has been used only as a laboratory instrument at this time.

A3.0 SURVEY OF APPLICATIONS

Contacts were made with a number of commercial firms which have had experience in sampling emissions from low velocity sources. This survey revealed that propeller or vane anemometers and rotating vane anemometers find the greatest popularity for low velocity sources. A few investigators also indicated the use of hot wire anemometers.

The popularity of these types of instruments is also reflected in the literature with regard to roof ventilators. Reference A5 cites the use of both hot wire (Anemotherm) and rotating vane anemometers and states that the latter type, either mechanical or electric models, are more convenient for general field use. Reference A6 reports a study in which propeller anemometers with electric output (Gill Model 27100) were successfully used for velocity measurements in roof ventilators.

EPA Method 14 (Ref. A7) specifies the use of vane or propeller anemometers with an electric signal output for velocity measurement in roof ventilator sampling. A single anemometer is to be installed at a point of average velocity, based on a widthwise velocity traverse, for each 85 m of roof ventilator length. Method 14 also specifies that the anemometers be able to withstand dusty and corrosive environments.

Pitot tubes were also used by some investigators for low velocity measurements. The use of a purge gas system with an S-tube was reported to be a useful means of approaching the problem, while an S-tube with a micromanometer reportedly was not successful for very low veloctiy testing.

In many cases, testing with the above-mentioned instruments has been done in conjunction with various types of protective screens, collection hoods, or flow straighteners. In addition, assessments of the accuracy of the instrumentation in these measurement applications are not available, since the actual flow rate and velocity distribution are not known in field applications. In short, the overall situation pointed to the need for further evaluation of the potential use of a number of instruments in low velocity applications.

A4.0 EVALUATION OF SELECTED INSTRUMENTS

A number of velocity measurement instruments were selected from the basic list given in Section A2.0 and evaluated as to their suitability for low velocity, unconfined source particulate sampling. Testing of these instruments was accomplished either in a model facility of a roof ventilator (Figs. A1 and A2) or in the field, measuring the flow from roof ridge ventilators atop a secondary aluminum foundry (Figs. A3 and A4). While field test evaluations provide a realistic view of actual conditions to be encountered in using the velocity instrumentation, it is not possible to determine the accuracy of an instrument in the field, as discussed previously. Thus, the roof ventilator model was used to determine the degree of reliability of the various instruments under conditions which simulated those existing in field applications. A summary of the tests of selected instruments follows.

A4.1 Vane Anemometer - Flowrite Model MRF

This instrument was tested both in the field and with the roof ventilator model. In the field test of the vane anemometer the instrument was fitted with an extension arm and hand held at the exhaust from the foundry roof ventilators. The instrument proved to be sufficiently rugged and easy to use under the awkward field test conditions, and velocity data obtained with the vane anemometer appeared to agree reasonably with expected results.

When tested in the same manner with the roof ventilator model, velocities were determined at 30 points in a plane at the exhaust from the model. The volumetric flow rate determined from these measurements was more than 100% greater than the actual flow rate supplied to the model. This large discrepancy was ascribed to the observed unsteady and circulatory flow emitting from the exhaust; since the vane anemometer cannot detect a reversed flow, the total velocity indicated by the anemometer is expected to be too large. Thus, this type of instrument was deemed unsatisfactory for use in circulatory flow patterns.

A4.2 Rotating Vane Anemometer - Davis Mechanical Vane Anemometer (Figs. A5 and A6)

This instrument was tested with the roof ventilator model, and volumetric flow rates determined from 24 point velocity surveys were compared with the actual flow rate

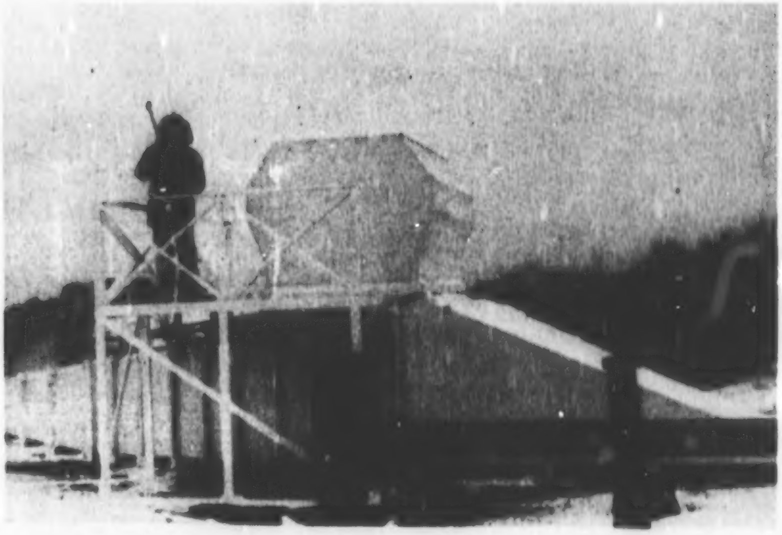


FIGURE A-1. ROOF MODEL LOCATED AT THE MEDICINE LAKE AERODYNAMIC TEST FACILITY - LOOKING SOUTH

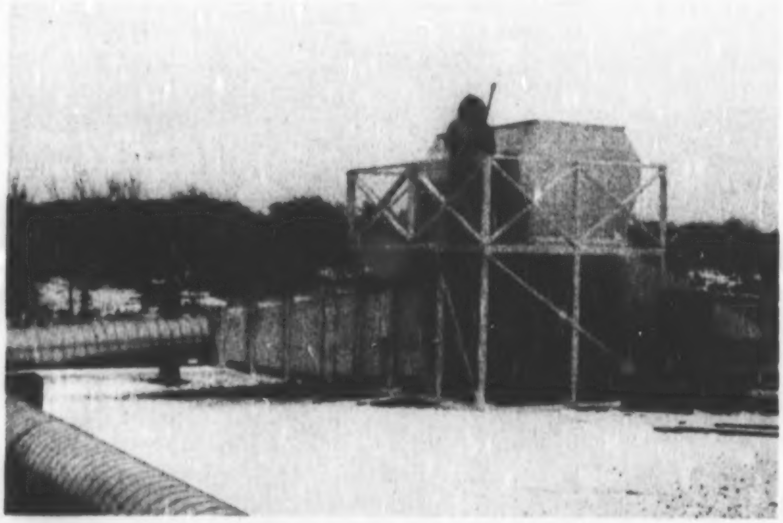


FIGURE A-2. ROOF MODEL AND DUCTING LOCATED AT THE MEDICINE LAKE AERODYNAMIC TEST FACILITY - LOOKING SOUTHWEST

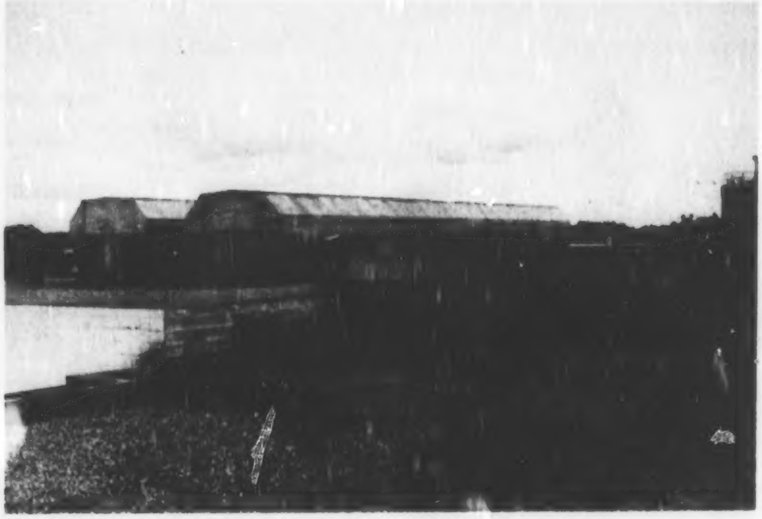


FIGURE A-3. ROOF VENTILATORS AT HITCHCOCK INDUSTRIES, BLOOMINGTON, MINNESOTA, VIEWED FROM THE NORTHWEST

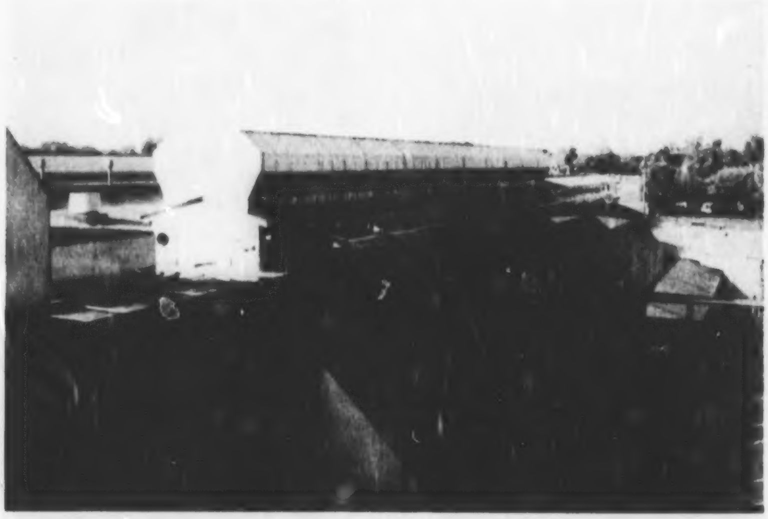


FIGURE A-4. ROOF VENTILATORS AT HITCHCOCK INDUSTRIES, BLOOMINGTON MINNESOTA, VIEWED FROM THE EAST

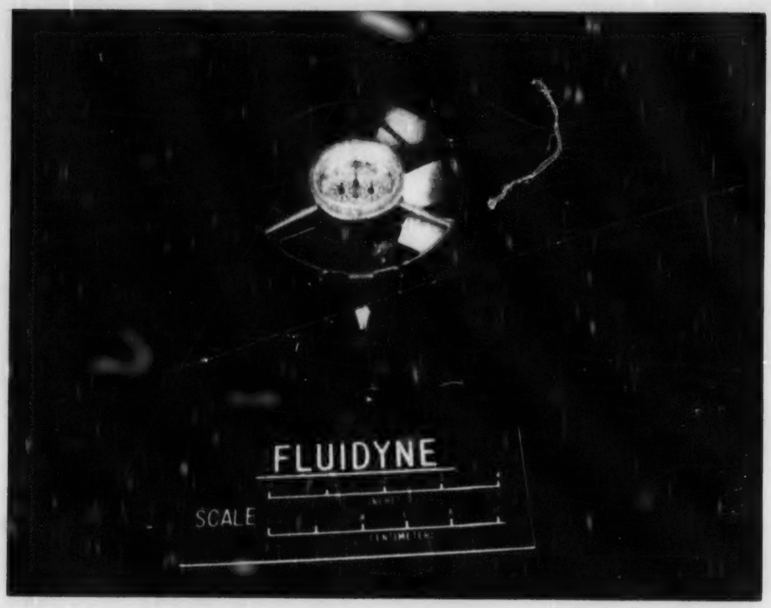

FLUIDYNE
SCALE
INCHES
CENTIMETERS

FIGURE A-5. DAVIS MECHANICAL ROTATING VANE ANEMOMETER WITH BALL SWIVEL ATTACHMENT

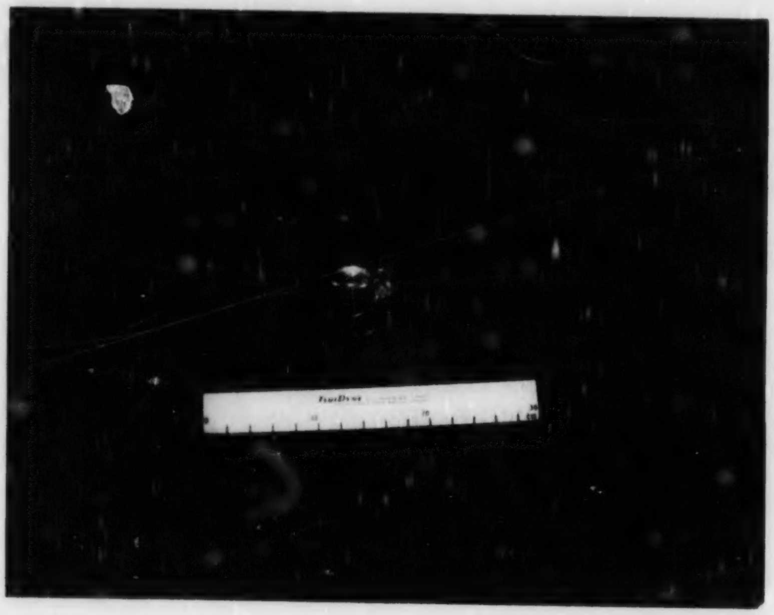


FIGURE A-6. DAVIS MECHANICAL ROTATING VANE ANEMOMETER WITH EXTENSION supplied to the model. The anemometer was fitted with an extension and hand held at the exhaust plane of the model. With this method, at flow rates ranging from about 75m^3/min to 200 m^3/min, the flow rate indicated by velocity measurements with the rotating vane anemometer and the actual flow rate differed by amounts varying from -25% to +75%. This lack of consistency was judged unacceptable.

A second measurement strategy was also evaluated with this instrument. In this method, the anemometer was inserted in the flow through sampling ports located at the base of the roof model. This location was deemed more appropriate for particulate sampling since the flow at the base of the model was observed to be more uniform and less dependent on wind conditions. A certain degree of circulatory flow was still present at the base of the model, however, due to the expansion of the inlet to the model downstream of the round ductwork which supplied the flow (Fig. A2). The flow at the base of the roof model could be made more uniform by insertion of a baffle in this diffuser section. Therefore, the flow entering the model at the base could be very uniform, with the baffle inserted, or somewhat circulatory, with the baffle removed. Both types of flow were observed at the field test site, related to the level of activity within the foundry, and the removable baffle thus allowed the simulation of both types of flow entering the roof ventilator model.

Volumetric flow rate determined from 24-point velocity surveys at the base of the model, made with the Davis anemometer, are shown in Fig. A7. As can be seen, the accuracy of the measurements is quite poor, although more consistent than the surveys made at the model exhaust. The results were somewhat better when the baffle was inserted, i.e., when the flow was more uniform, but in both cases the results were unacceptable.

A4.3 Hot Wire Anemometer - Thermo-Systems Model 1610

This instrument was fitted with a special protective collar used successfully in previous studies in which velocities from 0.03 to 4.5 m/sec were measured. However, the instrument still proved to be too fragile for use in the field. When tested at the aluminum foundry, the measurement probe was quickly damaged and the instrument rendered inoperable. Therefore, the hot-wire type anemometer was judged inadequate for field work in roof ventilator sampling.

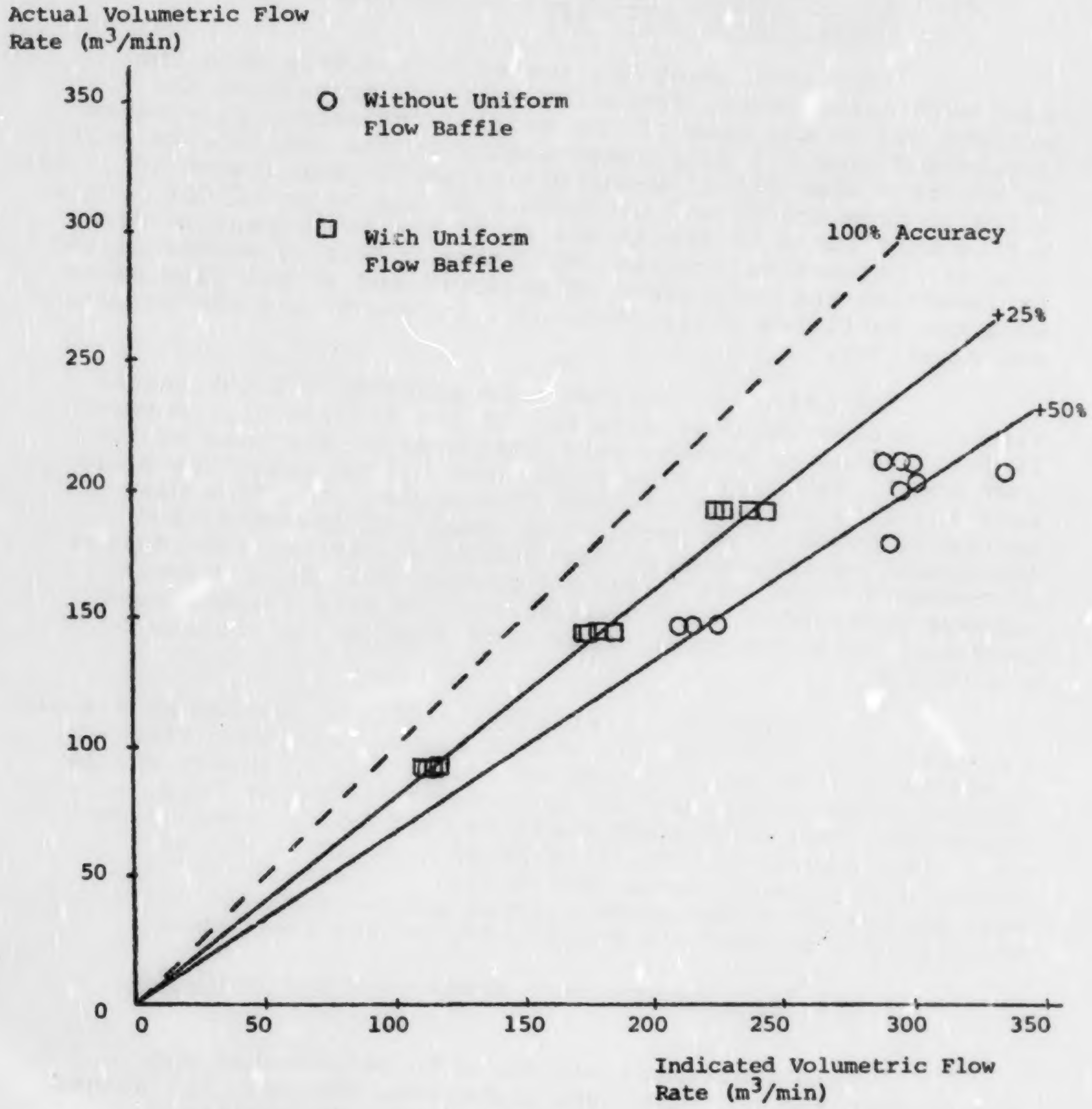


FIGURE A-7. VOLUMETRIC FLOW RATE AT BASE OF ROOF VENTILATOR MODEL DETERMINED WITH DAVIS MECHANICAL ROTATING VANE ANEMOMETER

A4.4 Hot Thermopile Anemometer - Hastings-Raydist Model PCI-30 (Fig. A8)

This instrument was tested extensively with the roof ventilator model, including velocity surveys at the exhaust and at the base of the model. Volumetric flow rates determined from velocity measurements at the exhaust, as well as the base when the flow-uniformity baffle was absent (Fig. A9), differed from the actual by amounts on the order of 60%. This may be attributed to the inability of the instrument to distinguish between velocities 180° apart. This is substantiated by observing the comparison of measured and actual flow rates with the baffle in place (Fig. A9), in which case the agreement was excellent.

In order to overcome this problem, a light weight flow direction tuft was attached to the instrument. Several 24-point velocity surveys were then made at the base of the roof model, using the flow direction tuft to align the probe with the flow and estimate the flow angle. The flow was generally found to be vertically upward or downward, and incorporating the uniform flow baffle eliminated the regions of downward flow. As indicated by Fig. A9, these velocity surveys provided a total volumetric flow rate which agreed very well with the actual flow rate even in the absence of the baffle.

The directional sensitivity of the instrument was also examined (Figs. A10 and A11), and it can be seen that flow direction (to 0° or 180°) can be determined by observing the output of the anemometer if the protective cap is used. Therefore, this instrument could be used to determine flow direction without a tuft, if a means were available to distinguish between flows 180° apart. Pulsating readings make alignment of the probe without a tuft somewhat difficult, however, due to the high sensitivity of the instrument.

A4.5 Hot Film Anemometer - Thermo-Systems Model 1650 (Fig. A12)

This instrument was found to be somewhat more rugged than the hot wire type anemometer and was lightweight and easy to handle. It was observed that in regions of pulsating or reversed flow, the response time of the instrument was very fast, making reading of the velocity difficult. In two tests of the instrument at the base of the roof ventilator model, with the uniform flow baffle in place, volumetric flow rate determined with the hot film anemometer was less than the actual flow rate by an average of only 3%. This instrument would also need an additional means for determining flow direction in a circulatory flow field.

FIGURE A-8. HASTINGS/RAYDIST PCI-30 HOT THERMOPILE ANEMOMETER WITH METER AND EXTENSION

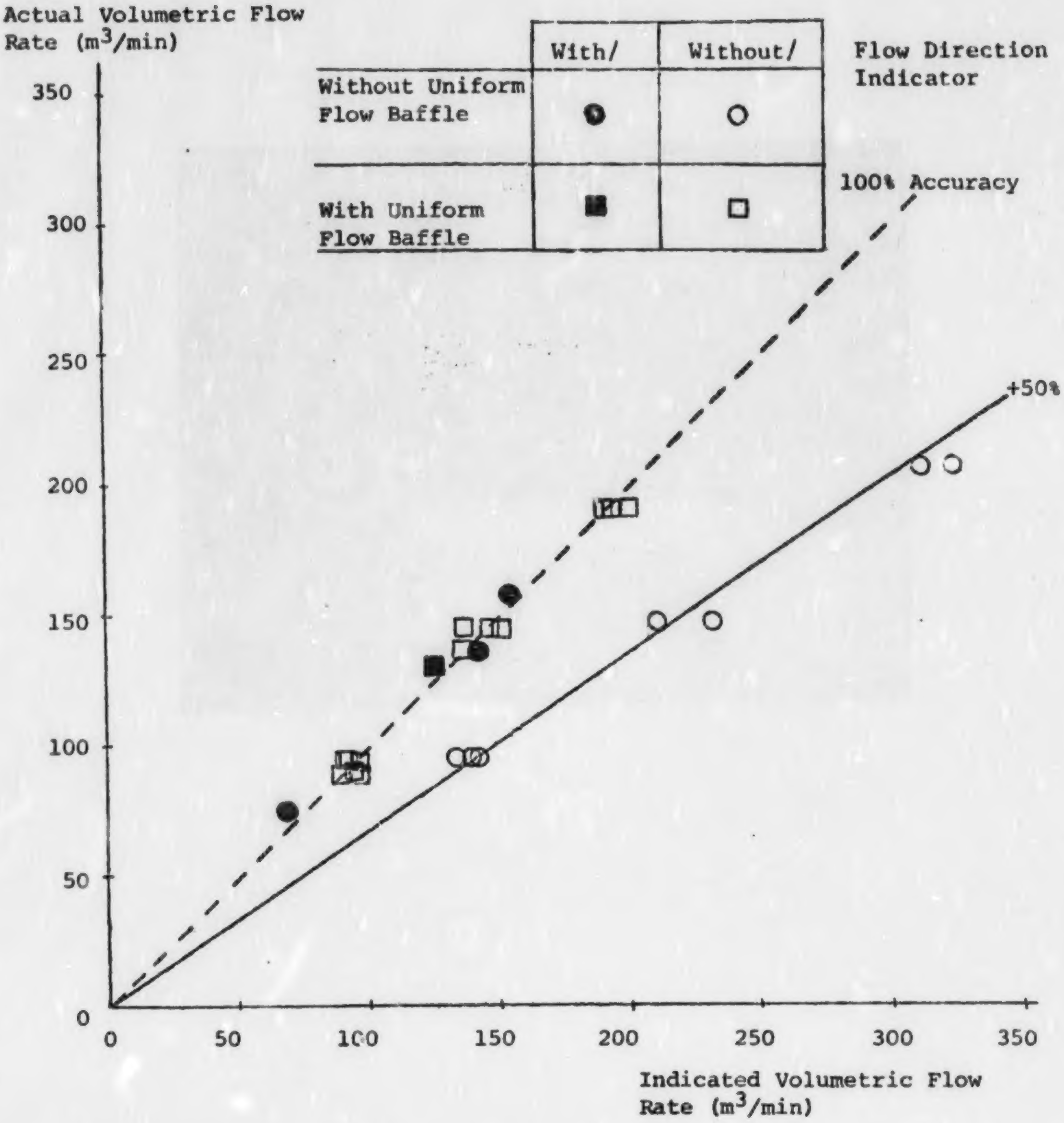


FIGURE A-9. VOLUMETRIC FLOW RATE AT BASE OF ROOF VENTILATOR MODEL DETERMINED WITH HASTINGS-RAYDIST PCI-30 HOT THERMOPILE ANEMOMETER

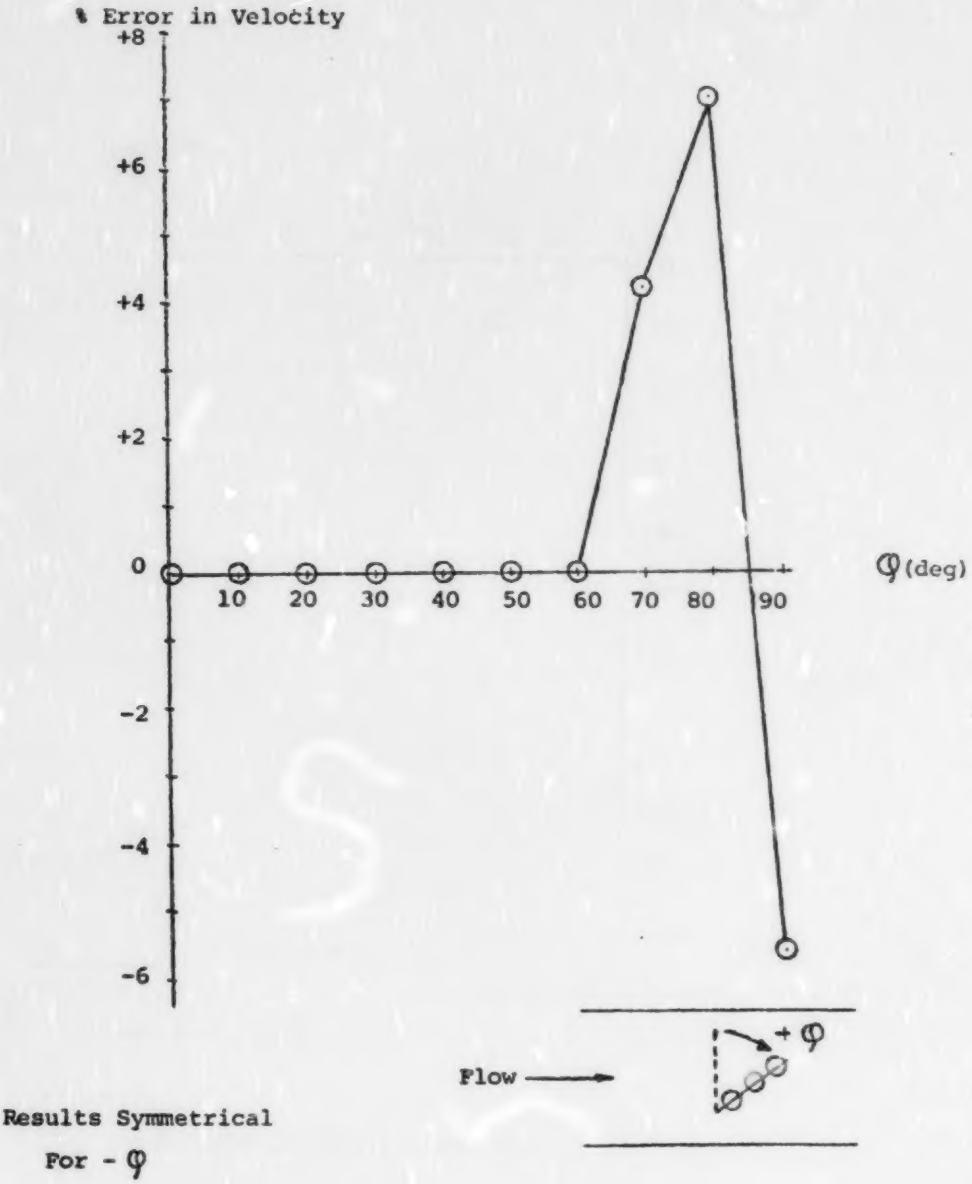
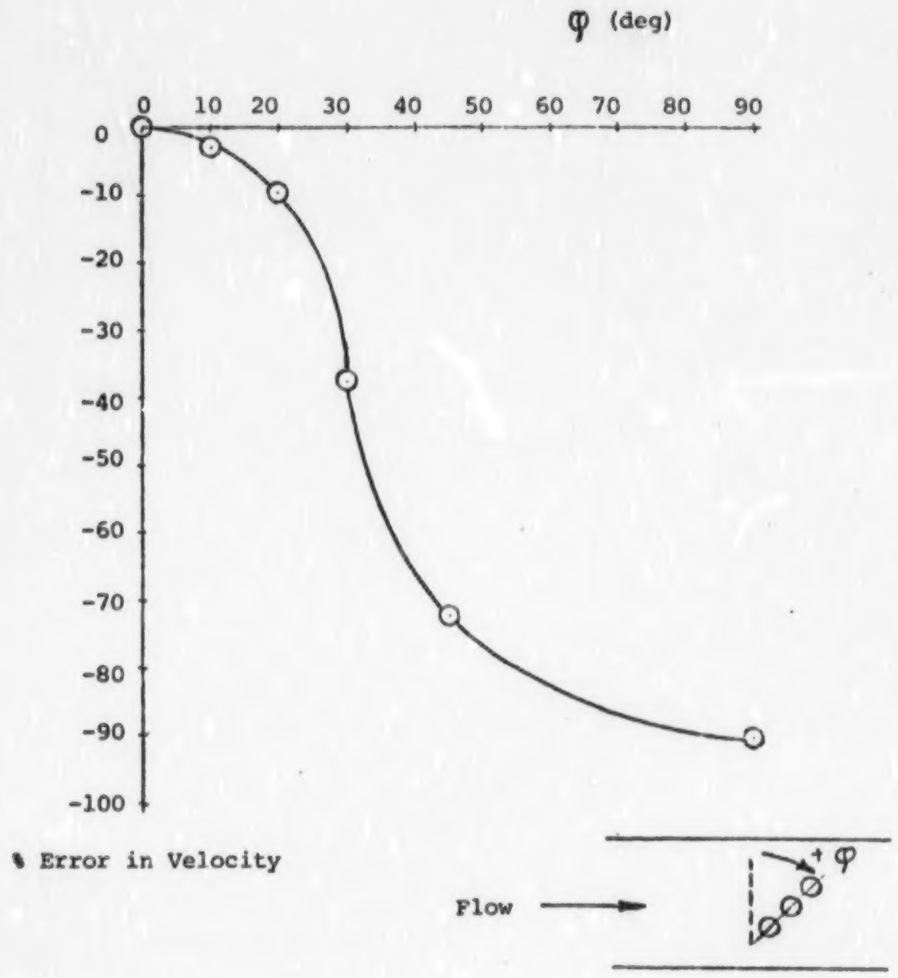


FIGURE A-10. VELOCITY ERROR WITH YAW ANGLE FOR HASTINGS-RAYDIST PCI-30 HOT THERMOPILE ANEMOMETER - WITHOUT PROTECTIVE CAP



RESULTS SYMMETRICAL FOR - φ

FIGURE A-11. VELOCITY ERROR WITH YAW ANGLE FOR HASTINGS-RAYDIST PCI-30 HOT THERMOPILE ANEMOMETER - WITH PROTECTIVE CAP

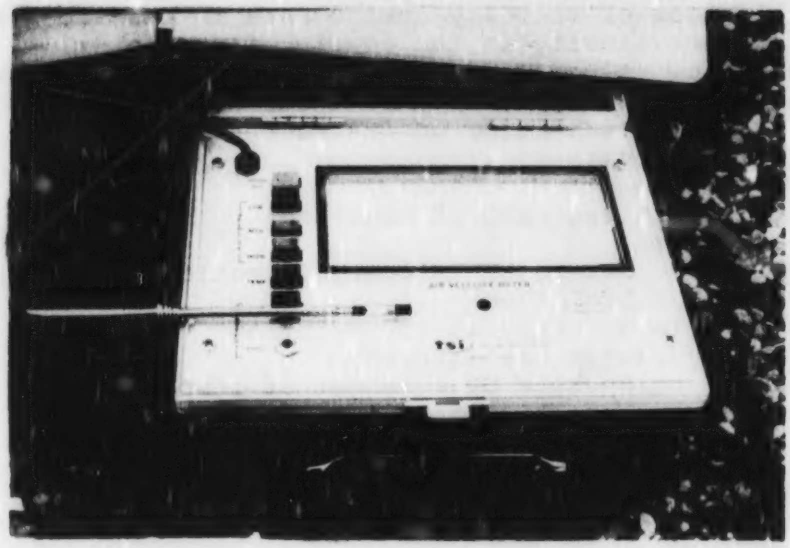

AIR VELOCITY METER
TSI

FIGURE A-12. THERMO-SYSTEMS, INC. MODEL 1650
HOT FILM ANEMOMETER

A5.0 CONCLUSIONS AND RECOMMENDATIONS

The most immediate observation that can be made from the above evaluation of velocity instruments is that accurate measurement of the velocity in the complex flow fields related to such low velocity, partially confined sources as roof ventilators is a very difficult matter. Several factors must be considered in selecting an instrument for such an application, among them:

1) versatility and ease of handling;
2) ruggedness;
3) ability to determine velocity direction as well as magnitude;
4) reasonable accuracy at the very low velocity ranges encountered;
5) ability to operate over ranges of temperature and particulate concentration.

Additional limitations may be placed on the selection of velocity instrumentation by cost considerations.

Considering these overall criteria, and on the basis of the evaluations described above, the most likely candidate for general velocity measurement in low velocity, partially confined sources is the hot thermopile anemometer (Hastings-Raydist Model PCI-30). This instrument is relatively lightweight and easy to handle, is very rugged, showed excellent results when used in relatively uniform flow and when used with a flow direction tuft, and operates reasonably well over a fairly broad range of temperature and particulate loading. In addition, the ability to determine flow direction could be utilized in circulatory flow if a means were available to distinguish between flows 180° apart.

The instrument may not be applicable to certain specific applications, however, such as low velocity sources with very high gas temperatures. The overall list of instruments shown in Table AI may be used as a guideline for selection of more appropriate instrumentation in such cases.

A6.0 REFERENCES

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